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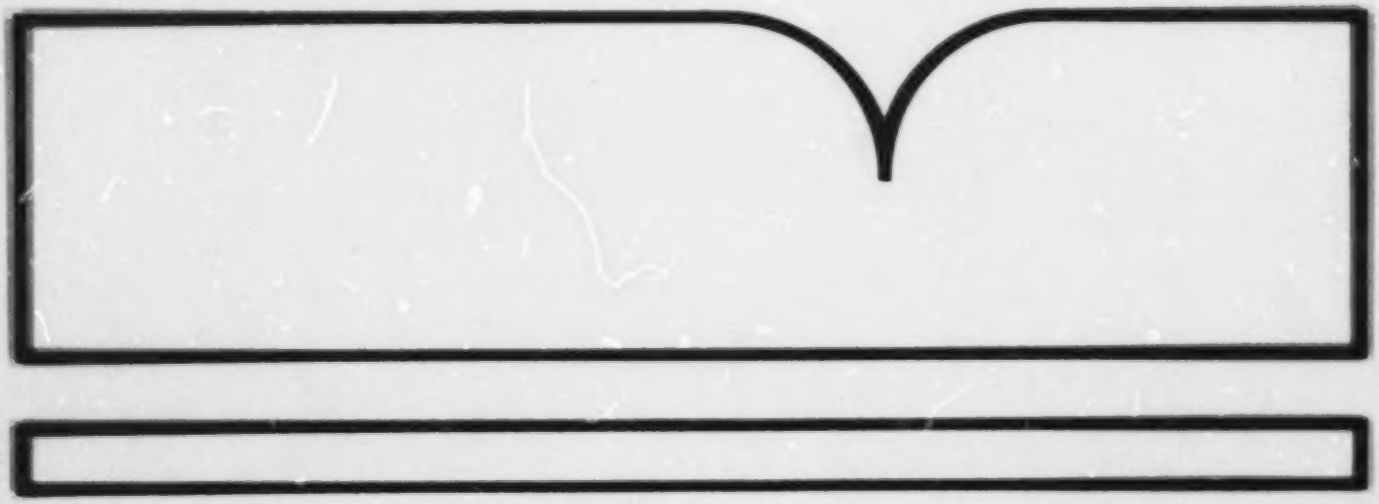

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A WORKSHOP REPORT ON THE COMPLEX TERRAIN MODEL DEVELOPMENT PROJECT (February 4-6, 1986)

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16. ABSTRACT

The Complex Terrain Model Development project is being sponsored by the U.S. Environmental Protection Agency (EPA) to develop atmospheric dispersion models to simulate air pollutant concentrations in complex terrain that result from emission from large sources. In early October 1985, an initial version of the Complex Terrain Dispersion Model (CTDM) was delivered to EPA. A major step in the evaluation of CTDM was a workshop that was conducted in February 1986. Each participant was provided a diskette or tape of the CTDM code and a draft User's Guide and was asked to exercise the model to assess its overall effectiveness and validity. Each person gave a one-half hour presentation of his findings. This report discusses the recommendations of the workshop participants.

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PREFACE

The Atmospheric Sciences Research Laboratory (ASRL) conducts intramural and extramural research programs in the physical sciences to detect, define, and quantify air pollution and its effects on urban, regional, and global atmospheres and the subsequent impact on water quality and land use. The Laboratory is responsible for planning, implementing, and managing research and development programs designed to quantify the relationships between emissions of pollutants for all types of sources with air quality and atmospheric effects, and to uncover and characterize hitherto unidentified air pollution problems. Information from ASRL programs and from the programs of other government agencies, private industry, and the academic community are integrated by the Laboratory to develop the technical basis for air pollution control strategies for various pollutants.

The Complex Terrain Model Development (CTMD) program is designed to develop reliable atmospheric dispersion models that are applicable to large pollutant sources located in complex terrain. Three major field studies were conducted during this six-year program. The first field measurements were collected at Cinder Cone Butte near Boise, Idaho during the fall of 1980. The second experiment was conducted at the Hogback Ridge near Farmington, New Mexico in October 1982. The third series of experiments were conducted in November 1983 and August 1984 at the Tracy Power Plant near Reno, Nevada. Data from these field studies along with measurements of fluid modeling and simulations performed in the EPA Fluid Modeling Facility are being used to develop the Complex Terrain Dispersion Model (CTDM).

In early October 1985 an initial version of CTDM was delivered to EPA. A final version will be delivered in August 1987. Over the next several months, CTDM will be modified and will undergo extensive evaluation. A major step in the evaluation of CTDM and its evolution toward becoming a regulatory model was a workshop that was conducted in February 1986. The workshop was attended by the model developers, EPA, other regulatory agencies, air quality consultants and university scientists. Each participant was provided a diskette or tape of the CTDM code, a draft User's Guide and the Fifth Milestone Report and was asked to

exercise the model to assess its overall effectiveness and validity in whichever way they chose. Each participant gave a 1/2-hour presentation of his findings. After the presentations, the participants were partitioned into three workgroups to discuss: (1) CTDM algorithms, (2) applications and practical considerations of the model, and (3) evaluation of the model. This report discusses the recommendations of the workshop participants.

ABSTRACT

The Complex Terrain Model Development (CTMD) project is being sponsored by the U.S. Environmental Protection Agency (EPA) to develop atmospheric dispersion models to simulate air pollutant concentrations in complex terrain that result from emission from large sources. The emphasis of the program is to develop models with known accuracy and limitations for simulating 1-hour concentrations in high terrain during stable conditions. To support the model development activities, four major tracer and flow visualization field experiments have been conducted since September 1980. The resulting data bases and data from towing tank and wind tunnel studies, conducted at the EPA Fluid Modeling Facility, and our understanding of the physical processes have been used to develop the Complex Terrain Dispersion Model (CTDM).

In early October 1985 an initial version of CTDM was delivered to EPA. A final version will be delivered in August 1987. Over the next several months, CTDM will be modified and will undergo extensive evaluation. The delivery of the final model will include estimates of the accuracy and precision of the model and an assessment of its overall limitations.

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- CTDM algorithms,
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LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOL	
C	Concentration
C_o	Observed concentration
C_p	Modeled concentration
χ	Concentration
f	Coriolis parameter
f	Subscript that signifies flat terrain
Fr	Froude number based on hill height
h	Terrain elevation above a reference elevation
h_o	Height of the zero-plane above the elevation defined as zero in the coordinate system being used
H_c	Critical dividing-streamline height
H_s	Plume height
i_x, i_y, i_z	Turbulence intensities alongwind, crosswind, and vertical
θ	Potential temperature
ℓ	Scale of mesoscale eddies
L	Monin-Obukhov length
L	Horizontal scale of hill
m_a	Arithmetic mean
m_g	Geometric mean
N	Brunt-Vaisala frequency
N	Number of observed concentrations
p	Hill shape profile exponent
Q	Source strength (mass flow rate)
r_a	Ratio of standard deviation of difference of modeled and observed concentration to standard deviation of modeled concentration
R	Correlation coefficient
s_g	Geometric standard deviation
σ	Standard deviation
σ_g	Geometric standard deviation

SYMBOLS

σ_v	Standard deviation of crosswind velocity fluctuations about the mean wind
σ_w	Standard deviation of vertical velocity fluctuations
σ_y, σ_z	Crosswind horizontal and vertical standard deviation of tracer concentrations
t	Time
T_{hz}	Terrain factor for streamline distortion in the vertical direction
T_y, T_z	Ratios of streamline distortion factor to diffusivity factor
T_L	Lagrangian time scale
T_{LY}	Lagrangian time scale for lateral dispersion
u,v,w	Alongwind, crosswind, and vertical wind speeds
u'v',w'	Downstream velocity perturbations
u_*	Friction velocity
(x,y,z)	General Cartesian coordinates
x_o	Distance along wind direction from source to terrain at the elevation of H_c for the LIFT domain; distance to terrain at the elevation of the receptor for the WRAP domain
∞	Infinity

ABBREVIATIONS

ASCOT	Atmospheric Studies in Complex Terrain
ASRL	Atmospheric Sciences Research Laboratory
AWAR	Alongwind aspect ratio
BAO	Boulder Atmospheric Observatory
baseh	Height of the zero-plane of the hill function
CF_3Br	Freon 13B1
CARB	California Air Resources Board
CCB	Cinder Cone Butte
CTDM	Complex Terrain Dispersion Model
CTMD	Complex Terrain Model Development
CWAR	Crosswind aspect ratio
EPA	U.S. Environmental Protection Agency
EPM	EPRI Plume Model
EPRI	Electric Power Research Institute
ERT	Environmental Research & Technology, Inc.
expo	Hill shape profile exponent

ABBREVIATIONS

FMF	Fluid Modeling Facility
FSPS	Full Scale Plume Study
GLC	Ground-level concentration
HBR	Hogback Ridge
LIFT	Component of CTDM that simulates dispersion over terrain
MDA	Modelers' Data Archive
MSE	Mean square error
MSL	Mean sea level
$\mu s/m^3$	Micro-seconds per cubic meter
NOAA	National Oceanic and Atmospheric Administration
NYSDEC	New York State Department of Environmental Conservation
OAQPS	Office of Air Quality Planning and Standards (EPA)
OCD	Offshore and Coastal Dispersion Model
ppb	Parts per billion by volume
ppt	Parts per trillion by volume
PC	Personal computer
PDF	Probability distribution function
PG	Pasquill-Gifford
PNM	Public Service Company of New Mexico
rc	Distance from origin to center of hill
RDT	Rapid distortion theory
RTDM	Rough Terrain Diffusion Model
SF_6	Sulfur hexafluoride
SBL	Stable boundary layer
scale	Horizontal length scale of major and minor axes
SPEX	Stable Plume Experiment
SRC	Sigma Research Corporation
TAF	Terrain amplification factor
TEB	Terrain Effects Branch (EPA)
thtac	Direction from origin to center of hill
thtah	Orientation of major axis of hill
Tracy	Tracy Power Plant near Reno, Nevada
TRC	TRC Environmental Consultants, Inc.
TTLY	Lagrangian time scale for horizontal dispersion
TUPOS	Turbulence Profile Sigmas - a multiple source Gaussian dispersion algorithm using onsite turbulennce data
WPL	Wave Propagation Laboratory
WRAP	Component of CTDM that simulates dispersion around terrain

ACKNOWLEDGEMENTS

We would like to thank all the workshop participants for their dedication and interest in the Complex Terrain Model Development project. Each participant was given a copy of the Complex Terrain Dispersion Model (CTDM) code and was asked to run the model and test it in whichever way he chose. All the participants actually ran the model and performed useful tests and evaluations. They came to the workshop very well prepared and gave excellent presentations. The outcome was a highly successful workshop and a useful exchange of information among the model developers and reviewers.

SECTION 1

INTRODUCTION AND RECOMMENDATIONS

The Complex Terrain Model Development (CTMD) project is being sponsored by the U.S. Environmental Protection Agency (EPA) to develop, evaluate and refine practical models for calculating ground-level air pollutant concentrations in mountainous terrain. The emphasis of the project is to develop models with known accuracy and limitations for simulating 1-hour concentrations during stable conditions. To support the model development activities, four major tracer and flow visualization field experiments have been conducted since September 1980. The resulting data bases and data from towing tank and wind tunnel studies, conducted at the EPA Fluid Modeling Facility, and our understanding of the physical processes have been used to develop the Complex Terrain Dispersion Model (CTDM).

In early October 1985 an initial version of CTDM was delivered to EPA. A final version will be delivered in August 1987. Over the next several months, CTDM will be modified and will undergo extensive evaluation. The delivery of the final model will include estimates of the accuracy and precision of the model and an assessment of its overall limitations.

A major step in the evaluation of CTDM and its evolution toward becoming a regulatory model was a workshop that was conducted in February 1986. The workshop was attended by the model developers (personnel from ERT and Sigma Research), EPA, other regulatory agencies, air quality consultants and university scientists. Each participant was provided a diskette or tape of the CTDM code, a draft User's Guide and the Fifth Milestone Report (DiCristofaro, et al 1986, EPA Document Number EPA/600/3-85/069) and was asked to exercise the model to assess its overall effectiveness and validity in whichever way they choose. For example, some of the participants evaluated the model using SO_2 and meteorological data collected around electric generating plants, some performed sensitivity studies, and some compared model assumptions to theoretical and numerical model calculations. Each participant gave a 1/2-hour presentation of his findings. After the presentations, the participants were partitioned into three workgroups to discuss:

- CTDM algorithms,
- applications and practical considerations of the model, and
- evaluation of the model.

This report discusses the recommendations of the workshop participants.

The remainder of this section lists the key recommendations of each workgroup. Section 2 discusses the CTDM Algorithm Workgroup, Section 3 - the Applications Workgroup, and Section 4 - the Evaluation Workgroup. Appendix A lists the workshop participants and the titles of their presentations. Appendix B provides short summaries of the presentations. Unedited summaries (e.g., short reports, copies of viewgraphs, graphs, tables, etc.) are available from the Project Officer.

The key recommendations of the three workgroups are:

CTDM Algorithm Workgroup

1. The CTDM-formula for σ_z requires further evaluation; specific topics to be investigated include:

   (a) the ability of sodar to estimate the height of the surface boundary layer and to identify elevated layers in which a plume may be trapped;

   (b) spectral analyses of w-data to identify wave contributions to σ_w;

   (c) the validity of theoretical estimates of σ_w in the surface boundary layer;

   (d) the validity of the assumption that $\sigma_w = 0.0$ above the surface boundary layer

   (e) the model of Pearson et al. (1983); and

   (f) an evaluation of the algorithm with the SPEX dataset.

2. $T_{LY} = \infty$ and, therefore, $\sigma_y = \sigma_v t$.

3. For regulatory applications the Gaussian form of the crosswind distribution should be retained in CTDM, reflecting the general availability of one-hour average meteorological data. Other variants should be used when proper data are available.

4. The LIFT component of CTDM should differentiate among the inner layer, the rapid distortion theory (middle) layer and the outer layer. The model should include an internal boundary layer over elevated terrain.

5. The formulation of the T_z factor along the lines suggested by the Hunt and Mulhearn (1973) theory should be explored further.

6. LIFT should be modified to simulate the strong lateral deflections of streamlines near H_c.

7. Wind shear and stratification should be accounted for in the T-factor formulations.

8. Although no modifications to CTDM are recommended to handle travel time more rigorously, the user should be aware that problems arise when the source to receptor travel time becomes comparable to the averaging time.

9. While it is recognized that the inclusion of slope flow effects in CTDM is not within the current scope of the present phase of CTMD, it is recommended that model users be made aware of their potential influence on GLC, especially when the height scale of the topography exceeds 500m and the winds are less than 5 m/sec.

Applications Workgroup

1. CTDM should be delivered as a stand-alone model that handles the stable plume impingement problem. The model should be able to handle blocks of stable meteorological conditions so 3-hour and longer average concentrations can be calculated.

2. The workgroup strongly recommends that CTDM be eventually incorporated into a plume model (e.g., the tall stack plume model being developed by EPRI or the new EPA model TUPOS) that handles nonstable conditions. The group does not recommend its incorporation into existing regulatory models.

3. CTDM should be used primarily as a refined model and not an advanced screening model. There are existing regulatory models that can be used as screening tools.

4. Because CTDM is a refined model, we recommend that the appropriate meteorological data be collected to provide input data: vertical profiles of wind speed and direction up to plume

height, vertical profiles of temperature up to the top of the terrain under consideration, and turbulence statistics (σ_v and σ_w) near plume height.

5. If the plume height is below around 10L (10 times the Monin-Obukhov length), then perhaps low level (~10m) measurements could be used to characterize the SBL and to estimate CTDM meteorological input.

6. A CTDM preprocessor should be developed that includes objective procedures to parameterize terrain in the model.

7. CTDM should include case-study and graphical displays that will help the user clearly understand the model simulations.

8. The user's guide should explain the essential features of CTDM, including a description of the new features that distinguish CTDM from currently employed Gaussian plume models.

Model Evaluation Workgroup

1. Further work needs to be performed in developing the model before a large model evaluation effort is undertaken.

2. The statistical tests used in the evaluation of CTDM should be consistent with those used by OAQPS. Specifically, subsets of the tests OAQPS has used in prior model evaluations focusing on measures of bias and root-mean square error should be employed. In this way CTDM performance can be compared more readily with other model evaluations.

3. CTDM should be evaluated using data bases beyond those collected in the CTMD program. Confidence in the model will improve if good performance can be demonstrated for a range of terrain and meteorolgical settings similar to those encountered in regulatory practice. Data bases identified for possible use were Steptoe Butte, Warren Power Plant, Widows Creek Power Station, Bowline Power Station, Mt. Tom Power Station and the Westvaco Luke, Maryland Mill.

4. Model evaluation should continue with the FSPS data base with particular attention to the σ_z formulation. The Freon data base contains information which can be used to examine model calculations vs. ground-level observations. The Freon tracer plume was not affected by buoyant rise and buoyancy induced dispersion.

5. The limits of applicability of CTDM will need to be defined carefully. Some information on this can come from knowledge of theoretical limits (e.g., doesn't handle local drainage flows); other information can come by efforts of recommendation (3), above.

6. Finally, the workgroup recommended that sensitivity studies be performed to examine the effect of input errors on predicted peak concentrations. Inputs identified for evaluation in decreasing order of importance are: wind direction, vertical diffusion, shape and orientation of hill from source, dividing streamline height, plume rise, potential temperature gradient and horizontal diffusion.

SECTION 2

ALGORITHM WORKSHOP

Leader: D. Strimaitis

Members: W. Eberhard, R. McNider, W. Snyder, A. Venkatram, D. Xu, R. Yamartino

2.1 Overview

The task of the CTDM algorithm workgroup was to identify ways in which the theoretical basis as well as the operational structure of CTDM can be improved within the scope of the current program. Four areas were discussed: vertical dispersion, lateral dispersion, the terrain effects in LIFT, and long travel time considerations. Beyond the scope of the current program, the workgroup also noted the utility of numerical dynamic modeling in understanding the influence of slope flows, differential heating, and complex channeling on flow and dispersion in complex terrain. Recommendations of the workgroup are discussed in the following sections.

2.2 Vertical Dispersion

Very Stable Limit

The main problem that arises in estimating the growth of a plume in the vertical when the atmosphere is stably stratified centers around separating the effects of waves from turbulence. The formulation used in CTDM assumes that measured values of σ_w contain only the motion associated with turbulence. But measurements of σ_w alone do not provide sufficient information to separate waves from turbulence. The theory of Pearson et al. (1983) requires that heat flux measurements as well as σ_w be made at plume elevation in order to sort out the portion of the vertical motion that is able to transport material in the vertical. However, a preliminary attempt to test the theory on the FSPS database ran into difficulty in that many of the periods had counter-gradient transport of heat associated with them. These periods certainly were dominated by waves, but the theory could not be applied to them.

Three methods for improving our ability to estimate σ_z were discussed by the workgroup:

1) Employ acoustic sounder information to estimate the height of the surface boundary layer and to identify elevated layers in which a plume might be effectively trapped.

2) Perform spectral analyses of the w-data to identify the wave contribution to σ_w.

3) Estimate the height of the surface boundary layer from tower measurements and assume that the theoretical profiles of σ_w with height will provide an adequate estimate of σ_w due to turbulence. In particular, if the plume lies above the top of the boundary layer we might assume that σ_w is zero.

Important tests of the first two methods are scheduled to be completed by the NOAA Wave Propagation Lab in the next few months. These investigations are expected to provide answers to the following questions:

CAN THE SCATTERING PROFILE FROM THE ACOUSTIC SOUNDER PROVIDE INFORMATION ON THE VERTICAL GROWTH OF A PLUME ?

Earlier studies performed by WPL have shown that elevated layers of sodar scatter are associated with step-like features in the vertical profile of temperature. Strong scattering occurs in the presence of large temperature gradients, whereas weak scattering tends to be associated with the more nearly adiabatic layers bounded by these. It is thought that a plume emitted into the near-adiabatic layer might very well be trapped in the layer, so that the vertical extent of the plume would be bounded by the layers of strong scattering. W. Neff at WPL will test this supposition by comparing the height and vertical dimensions of the oil-fog plume sampled by lidar in the FSPS with the observed scattering layers.

CAN THE SODAR FACSIMILE RECORD INDICATE THE DEPTH OF THE SURFACE BOUNDARY LAYER ?

The acoustic sounder certainly provides some information in this respect, but its accuracy and dependability in locating the top of the surface layer is not known to any member of the workgroup. We therefore recommend that the analyses undertaken by W. Neff at WPL include the task of evaluating the use of the sodar record to estimate the depth of the surface layer.

CAN A SPECTRAL DECOMPOSITION OF THE W-DATA ROUTINELY ISOLATE THE TURBULENCE COMPONENT OF THE VARIANCE FOR USE IN CTDM ?

The WPL work plan calls for performing the spectral decomposition of the w-data collected by the sonic anemometers during the FSPS. At a minimum, this will be done for the instrument located at 150-m on the main tower. Plume growth as measured by the lidar will be examined with regard to the decomposition to see if the residual σ_w (i.e. the portion remaining after removing the influence of waves on the vertical motion) provides estimates of σ_z based on the algorithm in CTDM which are in better agreement with the observed behavior.

The third method for estimating σ_z that was listed earlier should be tested on the same dataset used in the WPL analyses, as well as other portions of the CTMD databases. Nieuwstadt (1984) has shown that the structure of tubulence in the vertical for the case of a stable boundary layer in which the turbulence is continuous can be analyzed using the concept of local scaling. If the turbulent fluxes do not vary in time, he finds an expression for the depth of the surface layer that was first suggested on the basis of dimensional arguments by Zilitinkevich (1972)

$$h = 0.4\ (u_* L/f)^{\frac{1}{2}}$$

This expression has been found to provide reasonable estimates of h even when the surface boundary layer is not stationary. Venkatram (1980) and Nieuwstadt (1984) suggest a method for estimating h by this expression from rudimentary tower measurements.

If such estimates of h are found to be useful in characterizing the depth of the stable boundary layer in the complex flows typical of the CTMD datasets, or if estimates of h can be obtained from the sodar data, then the profile of σ_w might be estimated from

$$\sigma_w \simeq 1.3\ u_*\ (1 - z/h)^a$$

The value of a varies between 0.5 and 0.75. Note that this estimate of σ_w appears to apply only to the high-frequency component of the fluctuations, not the low-frequency, wave-like motions. Hence, this estimate of σ_w should be most relevent to the σ_z expression contained in CTDM when the measured σ_w is dominated by waves. Above h, turbulent diffusion is assumed to be absent in this formulation, and σ_w is set to zero. In implementing this type of approach in CTDM, careful consideration would need to be given to when the approximate estimate of σ_w should be given precedence over the measured value.

The σ_z expression in CTDM allows for an initial growth of the plume due to the turbulence associated with its buoyant rise. If this growth is great enough to dominate the effective growth due to the ambient fluctuations on all scales, then the use of the high-frequency σ_w in the CTDM σ_z expression to estimate the subsequent growth appears useful. But in the absence of this initial growth, some allowance must be made for vertical fluctuations on all scales (i.e. the measured σ_w) when estimating the initial growth of the plume. Therefore, a complete description of the dispersion process in very stable flows should be undertaken to improve the performance of the model for non-buoyant as well as buoyant sources.

To this end, the model of Pearson et al. (1983) should receive additional attention. When the heat flux at plume elevation is available, the method should be compared with the other analyses discussed above. Perhaps periods in which the heat flux is counter-gradient could be included by assuming that this type of heat flux is an indicator of substantial wave motion, and that there is no additional growth in the vertical size of the plume.

Weakly Stable Conditions

During the workshop presentations, W. Eberhard of WPL presented some initial comparisons of estimates of plume growth in the vertical, calculated by means of the CTDM algorithm, with observations of the growth of an oil-fog plume studied in the BAO Stable Plume Experiment (SPEX). The material presented indicates that σ_z may be significantly underestimated by the model. We spent some time looking at the data to understand why the estimates were so small for these periods. In general, the stable flow monitored in these periods tended to exhibit low-level jet-like structures, with significant gradients in both wind speed and turbulence.

The vertical structure in the flow is not treated in the model. Transport wind speed and turbulence at the height of the release determines the evolution of the plume. It was therefore thought that much of the discrepancy between modeled and observed plume growth might be explained by the lack of vertical structure in the model. However, the σ_w data measured during the two periods of substantial underestimation were so small that the plume remained very narrow. Consequently, little variation in σ_w or wind speed is expected across the depth of the plume.

As a result, no reason for the poor performance of the model could be readily substantiated. It was observed that the averaging times for the periods presented were short (on the order of 15 minutes), so that the travel time to the more distant sampling planes exceeded the averaging

times. Furthermore, no time-lags have been included as yet in the analysis to better associate the observed plume behavior with the meteorological measurements (this would seem desirable in view of the short averaging times). Therefore, due to the preliminary nature of the comparisons presented, the workgroup has refrained from suggesting specific modifications to the model, although it recognizes that further analysis of the SPEX database planned by WPL may suggest a problem in the model.

2.3 Lateral Dispersion

Lagrangian Time Scale

The current version of CTDM requires the input of a Lagrangian time scale, TTLY, for lateral dispersion. Estimates of this time scale vary enormously from several hundred seconds (Draxler, 1976) and up. However, it is most likely not a constant but rather proportional to l/σ_v where l is the length scale of the mesoscale eddies likely to influence the plume during the averaging time of interest. Plume travel time may also play a role. According to the Briggs (1973) representation, $\sigma_y = \sigma_v \, t/(1+x/x_o)$ where x_o = 10 km for all stabilities, suggesting a Lagrangian length scale notion and leading to a Lagrangian time-scale equal to:

$$T_{Ly} = 0.5 \; (x_o/u).$$

This leads to T_{Ly} = 5000 sec at u = 1 m/sec and T_{Ly} = 500 sec (i.e. the Draxler figure) at u = 10 m/sec. Given this wide range of T_{Ly} for flat terrain and the estimate that these values would increase in more complex terrain, the majority of the workgroup felt that a default value of T_{Ly} = ∞ (so that $\sigma_y = \sigma_v t$ and plume growth is always linear in time) is appropriate for CTDM. A minority of the group felt that a smaller default T_{Ly}, resulting in smaller σ_y, should be used in a regulatory model to ensure that concentrations are not underestimated and to ensure "consistency" with flat terrain model predictions.

Lateral Distribution

Several forms of the lateral distribution function in CTDM have been tested over the course of the CTMD program. The simplest form is the familiar Gaussian distribution function which is the form presently in use in the version of CTDM evaluated by this workshop. This form is used in conjunction with 1-hour average meteorological statistics, and also in conjunction with 5-minute average statistics when a 1-hour period is simulated by a sequence of 12 5-minute calculations.

Another version of the model employs a probability density function (PDF) derived from the 12 mean wind directions and the associated variances measured over an hour. In this formulation, a wind speed and a probability is associated with each degree of the compass, somewhat like a wind rose. Plume material is assumed to travel in straight lines so that the lateral distribution of concentrations is largely controlled by the PDF. As a result, there is no mean wind direction in the model. This formulation has been found to work well at the HBR site, especially in those instances when the wind field is highly variable, and the vector resultant mean wind direction is away from the hill.

A third major variant was presented at this workshop by S. Perry and D. Xu. They approached the problem of non-Gaussian wind direction distributions by allowing a bi-modal distribution in which each mode is assumed Gaussian. This differs from the PDF and the 5-minute methods in that plume trajectories are based on vector resultant winds for averaging periods of at least 15 minutes rather than 5 minutes (this averaging period can be specified on the basis of the travel time to important terrain features). Preliminary results show that this method improves modeled concentration patterns compared to the results of either the 1-hour Gaussian plume version or the 5-minute simulation version at HBR. No comparison has been made with the PDF approach.

The workgroup recognizes that each of the departures from the traditional 1-hour formulation requires meteorological data over intervals considerably shorter than 1-hour. Such a "refined" database is not routinely acquired at the present time, and any recommendation from the CTMD program that meteorological data be acquired routinely over intervals shorter than 1 hour must be accompanied by an estimate of the improvement in model performance that can be expected. Furthermore, users with "refined" databases acquired for model evaluation purposes should be able to access a version of the model that is able to take full advantage of the data. To this end, evaluation of the approaches already undertaken should be continued.

Application of the model using traditional 1-hour average meteorology will undoubtedly occur anyway. The workgroup feels that model evaluations using 1-hour data should utilize a "concentration fluctuation" model to address the likelihood that peak concentrations in a non-Gaussian distribution will exceed the peak modeled concentration.

2.4 Lift Algorithms

Much of the discussion on the basic structure of CTDM centered on

the LIFT algorithm. Material presented by workshop participants had indicated that LIFT tends to underestimate ground-level concentrations, particularly when compared to laboratory observations, and it also underestimates the degree of lateral distortion of thin plumes near the base of the (cut-off) hill. Furthermore, in the limit of very weak turbulence and hence limited plume growth in the vertical, the structure of LIFT allows only a vanishingly small terrain-effect on ground-level concentrations when the plume lies primarily above H_c. Because this workgroup recommends that σ_w be set to zero in very stable flows, we believe that LIFT will tend to underestimate ground-level concentrations to a greater extent if no other changes to the model are made.

Wind tunnel experiments presented by W. Snyder test the performance of LIFT in the unstratified limit, in which H_c is exactly zero. In the absence of a hill, these experiments showed that ground-level concentrations are estimated to within 30%. However, in the presence of a hill, these estimated concentrations are low by a factor of 2 or more. Two possible reasons for this are

1) neglect of wind speed shear in the formulation of σ_z, and

2) improper or incomplete specification of the effect of the hill on the turbulence in the flow and the resultant rate of turbulent diffusion.

The effect of wind speed shear on plume growth should be as evident in the results of the experiments in the absence of the hill as it is in the presence of the hill. But model performance in the presence of the hill is significantly worse, indicating that other effects may be of equal or greater importance. We looked at measurements of wind speed and turbulence over the hills (a 3-D axisymmetric CCB model and the 2-D "Russian Hill 5" model) to see if these were in approximate agreement with those assumed in CTDM. Turbulence intensity i_z is approximately constant in the flow nearest the surface, and decreases somewhat above this before returning to the intensity of the incident flow at even greater heights. This pattern conforms (both qualitatively and quantitatively) to the inner layer / rapid-distortion (RDT) layer formulas quoted by Britter et al. (1981). The version of CTDM evaluated at this workshop assumes that RDT applies to all elevations in the flow. Hence, it is recommended that CTDM be modified to differentiate between the inner, RDT, and outer layers of the flow. Furthermore, because the turbulence modifications are not very different from those assumed in the model, the formulation of the T_z factor along the lines suggested by the Hunt and Mulhearn (1973) theory should be explored further.

Experiments conducted in the stratified towing tank and reported by W. Snyder at the workshop test LIFT when H_c is non-zero. The flow above H_c is modeled as if it takes place over a hill reduced in height by H_c, and stratification is accounted for only to the extent that plume growth in the vertical is reduced and flow separation in the lee may be retarded. The comparison shows that CTDM underestimates ground-level concentrations in general (especially when the plume lies entirely above H_c) and does not spread the plume along the entire surface of the hill above H_c when the plume is very near H_c. These results suggest that:

1) an assessment be made of the influence of stratification on the degree of flow distortion over the hill in these experiments,

2) LIFT be modified to simulate the strong lateral deflections of streamlines near H_c, and that

3) an internal boundary layer be incoporated.

Suggestion 1 requires that streamline height calculations made on the basis of the theory reviewed at the workshop by R. Yamartino be compared with streamline elevations observed over the hills used in the tow-tank experiments. If the distortion is greater than that consistent with potential flow, then the T_z factor in LIFT would increase, thereby increasing ground-level concentrations. Also, any boundary layer formulation (suggestion 3) would rely on an adequate representation of the distorted flow field because the boundary layer mechanism for increasing concentrations at the hill surface depends on the speed of the flow and the proximity of the plume centerline to the top of the boundary layer.

Suggestion 2 requires that some alterations be made to the way the terrain factors are implemented. Potential flow over an ellipsoid posesses a stagnation point near which streamlines suffer large deflections in spreading over the surface of the obstacle. This extensive spreading of the flow is observed in both neutral flow wind tunnel experiments and in tow-tank experiments simulating stratified flow above H_c. However, this spreading is not well represented in LIFT because the minimum streamline elevation (upwind of the hill) is set to 5% of the cut-off hill height in computing the extreme terrain factors, and the factors themselves are bulk factors for the flow between the surface and the plume centerline. The first of these restrictions can be removed without changing the underlying structure of LIFT, but removing the second restriction may require extensive modification.

Suggestion 3 represents a conceptual change to the theoretical foundation of LIFT. Inclusion of a surface boundary layer driven by the changes in the flow induced by the terrain obstacle provides a mechanism for mixing plume material to the surface of the hill even if the ambient turbulence outside the boundary layer is very small. In effect, the mechanism provides a "two-layer" model of the vertical structure of the turbulence. When H_c is zero, the surface boundary layer is the "inner layer" in which i_z is approximately constant. In flows with strong stratification and non-zero H_c, the surface boundary layer is most simply implemented as a layer of large diffusivity which "eats" into the lower portion of an elevated plume. The requirement of a large diffusivity allows plume material below the top of the boundary layer to be uniformly mixed, thereby facilitating the estimate of ground-level concentrations.

2.5 Long Travel Times

CTDM in its present form does not include provisions for non-steady plume behavior such as recirculation or meandering when wind speeds are light. A number of problems arise when the source to receptor travel time becomes large compared to, or even comparable with, concentration averaging times or time durations for which the meteorological conditions (u, θ , σ_v, σ_w, N, etc) can be considered steady. This breakdown of assumptions associated with the Gaussian plume models can be remedied to a progressively greater degree by

a) use of time-lagged meteorology or
b) transition to a multiple Gaussian puff model.

The use of lagged meteorology is considered merely a pragmatic "fix" while a true puff model with changing meteorological conditions is beyond the scope of the current effort. It was the opinion of many that CTDM should not be modified to deal with this but that a warning message be generated in the model output for source-receptor travel times exceeding the averaging time. This warning would be most useful to ensure that concentrations for such time periods would not be given substantial weights in time and space model comparisons.

Long travel times in complex terrain may also present a problem even when the flow is steady. The flow may be channeled by terrain so that plume directions are not straight-line. Also, the flow may bifuricate several times around terrain obstacles so that Gaussian distributions are inadequate. Over such long distances puff or trajectory models may be more appropriate. The user's guide should stress that CTDM, formulated as a Gaussian plume model for simulating the plume impingement process, is primarily applicable to strong plume-terrain interactions on nearby hills.

Plume growth in the vertical may also require additional modification in the limit of large travel time. In this context large travel time is defined according to the size of σ_z relative to the vertical scale of boundary layer features. The present equation for σ_z assumes homogeneity in the vertical. Therefore it is not likely to be valid when σ_z becomes comparable to the vertical scale of variation of σ_w, N, etc. Possible methods of handling this inhomogeneity have been discussed in the Fourth Milestone Report (Strimaitis et al, 1985) and in Venkatram and Paine (1985). It is also important to note in this regard that the height of the SBL limits the vertical extent of σ_z. If the plume is released inside the SBL, this feature needs to be considered in estimating concentrations at large distances from the source.

2.6 Numerical Dynamic Modeling

Numerical dynamic modeling should be viewed as a tool to simulate flow and turbulent conditions in complex terrain much like the wind tunnel or tow tank. A numerical model could be used to extend the range of observations taken in the field or laboratory - such as to model larger scale terrain features, to simulate greater stabilities, or to include surface cooling. In the context of the CTMD program, numerical modeling has been used to address the role of drainage winds at the sites of the field experiments.

The initial field program at CCB (H~100m) showed that drainage flows were not a conspicuous feature. Numerical simulations substantiate this finding for CCB, but simulations for larger terrain (H~1000 meters) indicate that slope flows are substantial. Observations under the ASCOT field program also indicate that slope flows regularly exist on larger terrain features. In fact, the more stably stratified flow conditions at CCB and at the FSPS are attributed to drainage flows from terrain of larger scale . Local slope flows are most likely to develop in the early evening before substantial ambient stratification is established.

Numerical simulations for a two-dimensional ridge that is 1000 m tall indicate that for releases slightly above the critical dividing streamline a plume which would otherwise be carried over the ridge would be brought very near the surface by the downward vertical velocities produced by the drainage flow.

While it is recognized that inclusion of slope flow effects in the CTDM is not within the scope of the present project, it is recommended that users be aware of their presence. Specifically when the height scale of the topography exceeds 500 meters and ambient winds are less than 5 meters/sec then slope flows might be expected.

SECTION 3

APPLICATIONS WORKGROUP

Leader: T. Lavery

Members: R. Paine, L. Sedefian, G. Holzworth, M. Garrison, R. Williams, K. Wagner

3.1 Overview

The objectives of the working group on practical applications of CTDM were as follows:

- recommend the form of the model product to be delivered to EPA, both in the near term (1987) and the future;
- provide guidance for meteorological input data that the model system will need;
- recommend methods for the input of terrain information to CTDM;
- give recommendations for user documentation and special model case-study output that would help users to better understand CTDM.

3.2 Operational Model Form

The scope of this phase of the CTMD project requires that the CTDM that is delivered to EPA handle stable meteorological conditions. There is no requirement for a model that simulates a time series of hourly meteorological conditions -- stable and nonstable. However, this subgroup recognizes that the efforts of the past several years (as contained in CTDM) will be put to the most widespread use if the model can be easily adapted into a regulatory framework ,i.e., a model which can be utilized to determine compliance with ambient air quality standards.

Therefore, this subgroup recommends (1) the delivery of an initial, stand-alone model that handles stable conditions only, and (2) the

subsequent incorporation of CTDM into a new model that includes state-of-the-art methods to simulate nonstable events, e.g., convective and high wind speed conditions. The initial model should be able to handle at a minimum blocks of hourly stable meteorological conditions so the user can calculate three-hour and longer concentrations. The subgroup acknowledges the work being sponsored by EPRI and EPA to develop improved models for convective and windy boundary layers over flat terrain. We recommend that CTDM be eventually merged into the EPRI plume model (EPM). EPA (Turner 1986) is also working on an advanced Gaussian plume model (TUPOS) that could be used as a framework for CTDM. Also, the subgroup recognizes that little work has been done on dispersion in complex terrain during nonstable conditions. The CTMD data bases* include neutral, windy and convective cases, as well as stable conditions. We recommend that these cases be eventually analyzed and a model be developed for them. The final model should be based on the latest understanding of dispersion for all weather conditions — in complex and flat terrain.

In short, the three elements of an "all-inclusive" model are: a stable model for complex terrain (CTDM), a model that handles all weather conditions in flat and gently rolling terrain, and a model for unstable conditions in complex terrain (not currently covered by any model development projects). The ultimate regulatory model should include these elements. CTDM is the first step and will handle the stable plume impingement problem. The incorporation of CTDM into EPM or TUPOS is the next logical step. The third element should be accomplished under a future research project.

Of course, there are always weather conditions that cannot be handled by a standard model. For example, CTDM has not been designed to simulate the rise of a plume through a convective layer into an elevated stable layer with subsequent transport toward elevated terrain. The EPM also has not been designed to handle this situation; but a model called the Offshore & Coastal Disperion Model (OCD) includes an algorithm that at least attempts to handle such a situation. In any event, the best available modeling techniques should be combined to produce the "best" model. It should include CTDM.

A less desirable and possibly counter-productive mode of delivering CTDM is to incorporate the CTDM module into current regulatory models. We would recommend this alternative be pursued only if it can greatly expedite the adaptability of CTDM for regulatory purposes.

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* Other data bases e.g., ASCOT, should also be analyzed for these conditions.

Again, the goal of this phase of the CTMD project is to deliver an improved model for calculating concentrations in complex terrain. Therefore, the subgroup does not recommend using CTDM as an advanced screening model. A number of models already exist for that purpose. Perhaps, the screening models can assist in the selection of terrain features and meteorological conditions that should be modeled by CTDM.

The subgroup, while preferring that CTDM be used strictly as a refined model, recognizes that in some situations a complete meteorological data base (see next section) will not be available. In this situation the user and, if relevant, the reviewing agency meteorologist should determine the merits of applying the model with incomplete data.

3.3. Required Meteorological Input

Because we recommend that CTDM should be used primarily as a refined model, strict requirements for meteorological data are proposed. In general, users of CTDM will be required to obtain vertical profiles of wind direction and speed and temperature from near the ground to plume elevations and turbulence measurements at a height of at least the stack-top level. Profiles of meteorological variables such as wind speed, for example, are recommended to obtain good estimates of the critical dividing streamline height. Specific meteorological variables that will be required by CTDM are discussed below.

It should be recognized that for some situations low-level measurements may be sufficient to specify vertical profiles of wind direction, wind speed, turbulence and temperature. These can be modeled using the latest experimental results on the stable boundary layer. These estimates, however, are generally valid to heights of less than 10 times the Monin-Obukhov length, which are often well below plume height.

Although we do not want to specify exactly how the required meteorological measurements are to be made, our working group discussed the pros and cons of available measurement systems .

Wind direction

Studies have shown that CTDM predictions are very sensitive to wind direction, especially for thin plumes, even when the plume is being transported toward the terrain. For any plume, the ability for CTDM to determine whether a plume completely misses or impinges on a terrain feature depends upon the specification of a representative wind direction. Information about wind direction is especially crucial above

the surface layer, which is often quite shallow (less than 100 meters) during light wind, stable conditions. Therefore, users will need to have wind direction measurements, preferably near plume height, but at least at stack-top height.

Measurement systems for wind direction that were discussed by the group include conventional, instrumented meteorological towers and remote sensing methods (doppler acoustic sounders). The most desirable location for a meteorological tower or remote sensor would be in the undisturbed flow near the source and upwind of a terrain element. If height requirements preclude stack-height measurements from such a tower, it might be permissible to erect a second tower on elevated terrain. Measurements from the top of the second tower could be used if they were not affected by drainage flows or other local effects.

Wind speed

Wind speed profiles in the vertical are not well-organized during stable conditions, especially near complex terrain features. Low-level nocturnal jets, drainage flows, and other local phenomena make it difficult for a model to parameterize the wind speed change with height on the basis of a single, low-level observation. Wind speed measurements spanning the vertical extent of terrain features to be modeled are important for the accurate specification of the critical dividing streamline height.

Measurement systems mentioned above for wind direction are also appropriate for observations of wind speed. Use of measurements from elevated terrain should be used with caution. CTDM calculates terrain-induced modifications to the flow field. The use of data from towers in the distorted flow would be double-counting the distortion effects.

Turbulence measurements

Turbulence measurements are essential for estimating the vertical and horizontal extent of a plume. For several presentations at this workshop, these measures, especially vertical turbulence, had to be estimated by indirect means. These measurements should be more routinely taken for modeling applications to improve model predictions in the region above the surface layer (where parameterization of the turbulence does not work well).

The subgroup recognizes that the accurate measurement of vertical and horizontal turbulence is difficult, especially at stack-top or plume

elevations. There are even performance differences among systems currently in use (props, bi-vanes, etc.) that need some study. Unfortunately, turbulence data obtained from acoustic sounder systems during stable conditions are of questionable utility, although this problem may be alleviated with future improvements in the technology.

Measured values of σ_w can include contributions from waves that are difficult to remove. The use of measured σ_w values is discussed in Section 2.2.

Horizontal turbulence measurements are especially useful in determining the extent of plume growth and meander during the course of an hour. See Section 2.3.

Vertical turbulence measurements could be supplemented by data from facsimile records of acoustic sounder echoes. The presence of stable layers was shown in this workshop (Eberhard) to be correlated with limitations in the vertical growth of the plume. Inclusion of these layers in CTDM (perhaps a future version) may help to alleviate model overpredictions of σ_z for some cases. Facsimile records may also be used to determine the height of the stable boundary layer (See Section 2.2).

Vertical temperature gradient

The accurate representation of stable plume rise and the calculation of the dividing streamline height depend upon observations of the vertical profile of the potential temperature gradient. Current models used by EPA specify the gradient (a constant) as a function of the stability class. Observations tend to indicate, however, that the temperature gradient generally decreases with height in the stable boundary layer, and is somewhat unpredictable above the (often) shallow surface layer. Therefore, onsite measurements of the temperature gradient at heights encompassing the stack-top level as well as the vertical extent of the terrain features of interest are necessary. Temperature measurements on a tower provide information on the vertical profile of temperature but, of course, are limited to the height of the tower. Of course, balloon-based temperature sensors can provide the required data but are inconvenient operationally and are very labor intensive. Research is currently being conducted on remote sensing techniques to measure temperature to heights of 1000m. Perhaps in the near future remote sensors will be able to provide the required vertical temperature data.

Stability class

CTDM does not require a stability class as an input, since all measurements are provided and used directly.

Variables to be computed internally

The version of CTDM that was distributed prior to the Workshop required user input of several variables that will be computed internally by the operational version of CTDM. These variables include the following:

- final plume rise (obtained from the Briggs equations),
- distance from the stack to the point of final rise,
- σ_z of the plume at final rise,
- the dividing streamline height (computed for each hill separately),
- the Froude number for flow above the dividing streamline,
- the Brunt-Vaisala frequency (obtained from vertical temperature gradient data),
- the Lagrangian time scale for lateral fluctuations.

Again, it is intended that CTDM be used as a refined model. This will require the use of the meteorological input data discussed above. The workshop participants, however, recognize the inevitable use of CTDM without complete or representative data, despite several demonstrations that the model performs poorly without observations near plume height. The participants could not make firm recommendations on the use of the model with incomplete data. We feel it is up to the user to obtain the proper data bases. If the data are simply not available, the user should recognize the limitations. Also, if relevant, the reviewing agency meteorologist should work with the user to determine the merits of the data base for the specific application.

3.4 Terrain Specification

The input requirements of CTDM for terrain information are considerable, and have created some concern for the ability of a typical modeler to easily obtain the required data. Some problems and complications include:

- The model needs 3-dimensional hill shape information for all receptors involved in a run of CTDM. This data requirement results in a large amount of model preparation work. This preparation is justified for the use of a refined complex terrain model, but it is a challenge for the developers of an operational version of CTDM to minimize this preparation work while giving clear instructions that will minimize subjectivity in assembling the required information.

- The model can handle a limited set of idealized 3-dimensional shapes (i.e., horizontal sections are ellipses and vertical sections are inverse polynomials in shape). It is often difficult for a user to determine how best to parameterize real terrain.

- The determination of the hill-shape parameters often results in poor fits for various portions of an actual hill. It is currently up to the user to determine the best fit, a chore that should probably be done by CTDM itself or a preprocessor.

- If a receptor is on a hill that is itself part of a larger hill, it is not clear which part of the terrain (the smaller or larger hill) should be emphasized for a particular hour. The proper choice depends upon the plume size relative to the hill dimensions, the critical dividing streamline heights for each hill relative to the actual plume height, etc.

This subgroup made the following recommendations regarding the input of terrain features to CTDM. Actual implementation of these suggestions will depend upon their feasibility for use in CTDM with a minimum of structural changes to the model.

Input the terrain feature by performing the following steps:

- Select a position for the "crest" of the hill.

- Select a contour interval for specifying distances from the hill crest to each contour line in several directions.

- Tabulate distances from the crest to each contour line (some smoothing may have to be done) in several directions around the circle. Choice of directions may be guided by user estimates of major and minor axis orientations, or be fixed by the model.

- If the hill-shape parameters are to be determined by a preprocessor, specify the portion of the hill (direction, height) that should be given preference for weighting.

This method or a similar method of terrain input will result in more uniform results from user to user for the same terrain setting. The following data that are currently required from the user will be determined by CTDM or a preprocessor:

- rc, distance from the origin to the center of the hill; thtac, direction from the origin to the center of the hill;
- thtah, orientation of the major axis of the hill (some user input could be incorporated here);
- baseh, height of the zero-plane of the hill function;
- expo, scale.

3.5 User Documentation and Special Model Output

The model user's guide should explain the essential features of CTDM without an extensive technical description, and it should stress new model features that distinguish CTDM from currently employed Gaussian plume models. The supporting technical description of CTDM should be put into an appendix so as not to distract (and discourage) the user attempting to grasp the essential physical features of CTDM.

A thorough explanation of the meteorological input requirements of CTDM will be required. The results of model sensitivity runs can be mentioned to alert the user to what kind of errors in the input will cause significant model errors.

Several examples of actual terrain maps and how a user should input the terrain information to CTDM should be included in the user manual. The resulting shapes used by the model can also be illustrated.

The model output itself should include, at the user's option, several case-study and graphical results:

- hill shapes graphically represented with receptor locations shown,
- details of plume behavior for each source-receptor combination,
- predicted concentrations displayed graphically for each hill with receptors having nonzero concentrations.

These model displays will help the user to clearly understand what CTDM is using as input information as well as case-specific plume behavior and resulting concentration patterns.

SECTION 4

MODEL EVALUATION WORKGROUP

Leader: B. Egan

Members: N. Bowne, D. DiCristofaro, B. Lamb, R. Lee, S. Perry

4.1 Overview

This workgroup focused on providing recommendations on matters relating to the evaluation of CTDM as a model in an absolute sense and on the comparisons of CTDM performance with other models. The discussion concentrated on three areas:

- Evaluation of CTDM using existing data bases
- Statistical tests
- Sensitivity studies

4.2 Model Evaluation Data Sets

Evaluating CTDM with the FSPS Data Base

At this stage in the CTDM program, the model has been partially tested using the Tracy data base. Individual components of the model which need to be tested and evaluated are discussed below.

- σ_z Formulation (see Section 2.2). Observations and model calculations suggest that the specification of σ_z is an important component of the model. Observed σ_z data obtained from lidar and/or photographs must be compared with predicted values of σ_z. Measured values of σ_w directly affect calculated values of σ_z and, therefore, must be measured as accurately as possible. For some experiment hours the measured σ_w's are influenced by atmospheric waves. Is it possible to remove this wave component or should a new formulation be applied? Can σ_w be parameterized in some circumstances?

- σ_y Formulation. Predicted values of σ_y should be compared with the observed values obtained by lidar. This task is involved because it will have to be determined exactly what the lidar is observing when it estimates a value of σ_y.

- Comparison of CTDM - Calculated GLC with Observations. A total of 84 hours of lidar data have been processed by WPL. As many of these data as possible should be used to determine h, and the plume dimensions so that the model can be run. The modeling should focus on observed SF_6 concentrations on Beacon Hill and Target Mountain. Plume rise is not a factor in modeling the CF_3Br data base, so one variable (and the uncertainty associated with specifying it) has been removed, although the CF_3Br plume was not "visible" like the combined oil-fog/SF_6 plume. In any event, some modeling should be completed with the CF_3Br data base. The quality of the CF_3Br data base must also be evaluated.

- Case Study Analysis. The best way to assess the assumptions in CTDM is to study the meteorology and CTDM results on a case by case basis. Five to ten FSPS cases should be studied in detail. A variety of meteorological conditions and CTDM performance results should be used in the selection process. Then all meteorological data, photographs, time-lapsed movies, videotapes, lidar data, etc. should be assimilated to study the physics of the situation and subsequently evaluate the assumptions in CTDM.

Evaluating CTDM with Other Data Sets

Further evaluation of CTDM is recommended through the use of a number of available data bases, in addition to those from CCB, HBR, and Tracy. These sets include concentration and meteorological data from Warren, Westvaco, Widows Creek, Mt. Tom, and Steptoe Butte, among others. The data from these locations tend to be less complete than the data obtained from the CTMD, but the data from these other sites can be used to determine the sensitivity of the model to missing or incomplete data. Comparing the performance of the model using incomplete data sets with the performance of the model using a higher quality data set will highlight the most critical terms in the model. These performance tests will also provide insight into potential problems in the application of CTDM at a variety of different sites. In particular, these model studies will aid in setting the limits of applicability of CTDM. There are undoubtedly sites, such as sites with highly channeled valley flows, where CTDM should not be applied.

Preliminary results from the evaluation of CTDM using data from a number of sites were presented at the workshop and are summarized in Appendix B. Two different analyses were conducted for Westvaco. The hill shape parameters developed by two different analyses were quite similar for the Westvaco site. In one analysis, calculations of maximum concentrations on the ridge varied from nearly equal to approximately a factor of two greater than observed SO_2 concentrations at monitors on the ridge. Statistical performance measures for the second study are presently being evaluated.

An operational evaluation of CTDM at the Warren site yielded results which were much better than results from COMPLEX I calculations. However, the CTDM estimates differed from observed concentrations by a factor of four or more in some situations. At Steptoe Butte, results from a series of tracer experiments were used to test CTDM. The analysis indicated that optimal model performance statistics could be obtained by using the "maximum" wind direction and making reasonable adjustments in the vertical diffusion rates and, in some cases, the plume height or dividing streamline height. Together, these preliminary tests of CTDM show the utility of further model testing using external data bases.

The proposed evaluation tests are not intended to test specific CTDM submodels, since the data, in general, will not be available for detailed analysis of plume physics. The workshop also recognizes that the compilation of data and testing of the model with outside data sets may require time and effort beyond that available before the end of the current project. As a result, additional model evaluation beyond that which can be accomplished within the present program should be an immediate priority in the next phase of the CTMD. In the near term a model evaluation using only one or two of the available data sets should be performed. The Warren, Widows Creek, and Mt. Tom data sets are probably the most likely and useful candidates for evaluation. It appears that in each of those cases the data are in a form usable for CTDM application and each site respresents a real source located in complicated terrain.

The workshop also recommended that CTDM be evaluated with respect to other models. The best mechanism for this model vs. model comparison may be a modeling workshop where modeling results based upon a pre-selected, common data base are presented. This kind of model testing will be useful for evaluating different modules in CTDM in comparison to corresponding

modules in other models. Because of the time needed to coordinate this kind of comparison, the model vs. model comparison is considered a priority for the next phase of the complex terrain research.

4.3 Statistical Tests and Displays

Statistical tests used in the evaluation of CTDM should be consistent with those used by the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Fundamentally, the tests should provide a measure of bias and root-mean square-error of the model when compared to observations. Several tests are usually employed with various combinations of the data. We assume that the basic data base consists of a set of observed and predicted concentrations at the same location and for the same time period. The assumption is valid for a long series of air quality observations at a few sites or many tracer observations for a limited number of hours.

- Paired Comparisons. The most restrictive test of a model is the ability to correctly predict concentrations at specified locations for the time of observation. Statistical tests and displays employed for this situation consist of correlation coefficients, scatter plots, comparisons of maximum and average values and sometimes comparisons of second moments of ground level tracer concentration patterns. Positions of maxima for specific time periods may be examined for distance and direction. Correlations may be repeated after rotation of the axis to match the centerline of predicted and observed patterns.

- Paired in Time Only. The second most restrictive test involves comparison of the highest predicted and observed value from the field of receptors for each hour. Since no pairing of locations is required, errors in direction and distance to maximum are ignored in this comparison. Statistical tests and comparisons that are used include correlation coefficients, scatter plots and comparisons of average values and variances.

- Unpaired Comparisons. The third type of comparison ignores both time and location of predicted and observed values. This comparison yields information that some regulatory personnel use in their assessment of models. The types of comparisons employed include cumulative frequency distributions and comparisons of the top 5 percent of the distribution.

- Paired in Location, not in Time. A fourth comparison is pairing of data by location but without respect to time. The comparison shown for the individual sites at the Warren Station Network evaluation of CTDM presented by Bowne (Appendix B) was one example. Frequency distributions, scatter plots and the top five percent are all appropriate examinations just as used in the unpaired comparison tests.

  Another type of location pairing involves the definition of similar conditions, e.g., stability, wind direction and speed to measure capabilities of the model under those conditions. Statistical tests may be those employed for paired comparison or simply those for unpaired events.

- Other Statistical Tests. Tests that are employed to test the significance of differences must be used with caution. Parameter tests such as Student's t to test difference of means, or the F Test to measure differences of variances assume a normal distribution. Most of the distributions found in model evaluations are not normal. Therefore, comparisons are usually made with data from other studies, rather than using rigorous statistical tests.

  Correlation coefficients may be tested for differences from other data and for differences from zero. Statistical tests for differences of frequency distributions usually employ the Kolmogorov-Smirnov test.

  The best estimates of model performance for comparison with other evaluations remain a measure of bias and the scatter as measured by the root-mean-square error. Bias can be measured by mean value ratios or differences between observed and predicted values. Selection of the data to be used in the measures is the responsibility of the user but must be explained. Some users are interested in only the high concentration values and examine only the upper portions of the frequency distribution. Model performance is more fairly represented by considering the total data base.

4.4 Recommendations on Sensitivity Studies of CTDM

Sensitivity studies are needed to determine quantitative relationships between input data errors and the concentrations, especially the peak concentrations, calculated by the model. Such studies can be

used to help specify the degree of accuracy required in obtaining the data required by CTDM. Some variables may need to be prescribed accurately, while others may affect the results so little that crude estimates are adequate. Further, some cases may be identified which make greater demands on the accuracy of the input data than can be reasonably accommodated. Such a finding could provide a basis for defining limitations on the applicability of the model and also which CTDM components dominate the GLC for certain meteorological or terrain settings.

Some of the participants at this workshop have presented sensitivity analyses (Appendix B) of CTDM. These analyses have demonstrated the need for more complete sensitivity analyses of CTDM. Variables for which sensitivity studies are needed are given, in decreasing order of importance, as judged by this work group, as follows:

- wind direction,
- vertical diffusion,
- shape and orientation of the hill,
- critical dividing streamline height,
- plume rise,
- potential temperature gradient, and
- horizontal diffusion.

At least one presentation at the workshop showed significant effects on calculated concentrations due to errors in wind direction. Errors may be incurred when measurements are taken well below plume height, at a location removed from the source, or when trajectory changes between the source and the receptor occur in a manner not accounted for by CTDM. In some instances, especially with an elongated hill, it is not entirely clear whether errors in wind direction only misplace the location of the peak value, or substantially alter the peak value. This needs to be defined more quantitatively.

Vertical diffusion is calculated based on the vertical turbulence σ_w representative of plume height. This is not easily determined. Studies are needed to determine how accurately σ_w needs to be specified to produce accurate results both in the near field and far downwind. In addition, the effects of changing CTDM formulation for σ_z should be considered.

Defining the hill shape requires substantial judgment on the part of the modeler. This raises several questions that should be investigated. How serious are the effects of erring in the orientation of the major axis of a hill that is slightly elongated, and one that is highly elongated?

How much variation in calculated concentrations will result from say, five different people defining the shape parameters of a real hill? What is the net effect of using an objective or semi-objective computerized technique for determining some of these parameters? Separate analyses should be conducted for the orientation of the major axis and for the hill-shape exponents.

The critical dividing streamline height (H_c) is crucial to the operation of CTDM, yet is difficult to obtain in practice. Contributing to errors in the plume height-H_c differences are errors in estimating H_c itself and errors in estimating plume rise. Errors in specifying the potential temperature gradient will affect plume rise estimates, but this should be treated separately as described below.

The potential temperature gradient affects calculations of plume rise, Brunt-Vaisala frequency (N), Froude number (Fr), and critical dividing streamline height (H_c). The net effect of errors in specifying the potential temperature gradient should be investigated, allowing for the simultaneous effects on plume rise, N, Fr, and H_c.

The sensitivity of the calculated concentrations to errors in specifying horizontal diffusion should be determined. This would include not only σ_v, but also the effects of the horizontal Lagrangian time scale on concentrations from a few kilometers to a few tens of kilometers downwind.

To summarize, sensitivity analyses should be conducted to determine the effects of errors in the input data. These, beginning with the most important, are:

- wind direction, noting whether the effects of errors are to move the location of the peak only, or change its value as well;
- vertical diffusion, both as specified by the σ_w input, and the formulation of the model itself;
- definition of the hill shape and orientation described by different individuals, as well as by one or more objective or semi-objective techniques;
- plume height relative to the critical dividing streamline height;

- the potential temperature gradient, accounting simultaneously for its effects on plume rise, Brunt-Vaisala frequency, Froude number, and critical dividing streamline height; and

- horizontal diffusion, both as affected by σ_v and by the horizontal Lagrangian time scale, with regard to receptors from a few kilometers to a few tens of kilometers downwind.

REFERENCES

1. Briggs, G.A., 1973. Diffusion Estimation for Small Emissions. ATDL Contribution File No. 79, Atmospheric Turbulence and Diffusion Laboratory.

2. Britter, R.E., J.C.R. Hunt, and K.J. Richards, 1981. Airflow Over a Two-Dimensional Hill: Studies of Velocity Speed-up, Roughness Effects and Turbulence. Quart. J.R. Met. Soc., 107: 91-110.

3. DiCristofaro, D.C., D.G. Strimaitis, B.R. Greene, R.J. Yamartino, A. Venkatram, D.A. Godden, T.F. Lavery, and B.A. Egan, 1986. EPA Complex Terrain Model Development Program: Fifth Milestone Report - 1985. EPA/600/3-85/069, U.S. EPA, Research Triangle Park, NC.

4. Draxler, R.R., 1976. Determination of Atmospheric Diffusion Parameters. Atmospheric Environment. 10:99-105.

5. Hanna, S.R., L.L. Schulman, R.J. Paine, J.E. Pleim, and M. Baer, 1985. Development and Evaluation of the Offshore and Coastal Dispersion Model, JAPCA, 35:10:1039-1047.

6. Holzworth, G.C., 1980. The EPA Program for Dispersion Model Development for Sources in Complex Terrain. Second Joint Conference on Applications of Air Pollution Meteorology, New Orleans, LA. AMS, Boston.

7. Hunt, J.C.R., and R.J. Mulhearn, 1973. Turbulent Dispersion from Sources Near Two-Dimensional Obstacles. J. Fluid Mech., 61: 245-274.

8. Lavery, T.F., A. Bass, D.G. Strimaitis, A. Venkatram, B.R. Greene, P.J. Drivas, and B.A. Egan, 1982. EPA Complex Terrain Model Development Program: First Milestone Report - 1981. EPA-600/3-82-036, U.S. EPA, Research Triangle Park, NC.

9. Lavery, T.F., D.G. Strimaitis, A. Venkatram, B.R. Greene, D.C. DiCristofaro, and B.A. Egan, 1983. EPA Complex Terrain Model Development Program: Third Milestone Report - 1983. EPA-600/3-83-101, U.S. EPA, Research Triangle Park, NC.

10. Nieuwstadt, F.T.M., 1984. Some aspects of the turbulent stable boundary layer. Invited paper at the 20 Oholo Conference on Boundary Layer Structure, 25-28 March 1984, Israel (Submitted to Boundary-Layer Meteorology).

11. Ryan, W., B. Lamb,, and E. Robinson, 1984. An Atmospheric Tracer Investigation of Transport and Diffusion around a Large Isolated Hill. Atmospheric Environment, 18, 2003-2021.

12. Snyder, W.H., 1986. Comparsion of CTDM Calculations with Fluid Modeling Observations, U.S. EPA/ARSL, Research Triangle Park, NC.

13. Strimaitis, D.G., A. Venkatram, B.R. Greene, S. Hanna, S. Heisler, T.F. Lavery, A. Bass, and B.A. Egan, 1983. EPA Complex Terrain Model Development Program: Second Milestone Report - 1982. EPA-600/3-83-015, U.S. EPA, Research Triangle Park, NC.

14. Strimaitis, D.G., T.F. Lavery, A. Venkatram, D.C. DiCristofaro, B.R. Greene, and B.A. Egan, 1984. EPA Complex Terrain Model Development Program: Fourth Milestone Report - 1984. EPA-600/3-84-110, U.S. EPA, Research Triangle Park, NC.

15. Strimaitis, D.G., D.C. DiCristofaro, and T.F. Lavery, 1986. Users Guide For CTDM (27485), U.S. EPA/ASRL, Research Triangle Park, NC.

16. Turner, D.B., 1986. Personal Correspondence, U.S. EPA, Research Triangle Park, NC.

17. Venkatram, A., 1980. Estimating the Monin-Obukhov length in the stable boundary layer for dispersion calculations. Boundary-Layer Met., 19, 481-485.

18. Venkatram, A. and R. Paine, 1985. A Model to Estimate Dispersion of Elevated Releases into a Shear-Dominated Boundary Layer. Atmospheric Environment, 19:11:1797-1805.

19. Zilitinkevich, S.S., 1972. On the determination of the height of the Ekman boundary layer. Boundary-Layer Met., 3, 141-145.

APPENDIX A

WORKSHOP PARTICIPANTS

F.Schiermeier EPA	Introduction to the program
P. Finkelstein EPA/TEB	Overview of workshop goals and directions
B. Egan ERT	The CTDM program
T. Lavery SRC	Model development goals
D. Strimaitis SRC	The Complex Terrain Dispersion Model (CTDM)
A. Venkatram ERT	Diffusion in the stable boundary layer; and simplification of CTDM equations for semi-empirical modeling
W. Snyder EPA/FMF	Comparison of CTDM calculations with fluid modeling observations
W. Eberhard NOAA/WPL	The CTDM lidar data base; evaluation of σ_z-formula using the BAO data base
R. McNider U. of Alabama	Evaluation and Critique of CTDM
D. DiCristofaro SRC	Evaluation of CTDM using the FSPS MDA
M. Garrison EPA/ Region III	Sensitivity Tests at Westvaco. Model comparison and sensitivity tests using the Warren data set
R. Paine ERT	Results of CTDM Test Runs on Case Study Hills: Qualitative Comparisons
R. Lee EPA/OAQPS	An evaluation of CTDM using the CCB and Westvaco data bases and a comparison with COMPLEX I

L. Sedefian NYSDEC	An evaluation of CTDM, COMPLEX I and the NYSDEC models using the Roseton Station data base
N. Bowne TRC	Preliminary Tests of the EPA CTDM
R. Williams PNM	Meteorological data input and an evaluation of CTDM using the San Juan data base
K. Wagner CARB	Evaluation of the CTDM Air Quality Model
B. Lamb Washington State University	An evaluation of CTDM using the Steptoe Butte data base
R. Yamartino SRC	Stratified flow over 3-D hills
S. Perry, D. Xu EPA/TEB	Potential Improvements to the Model Specification of Wind Direction during Large Meander Periods

APPENDIX B

SUMMARIES OF WORKSHOP PRESENTATIONS

This appendix provides short summaries of the presentations. Original, unedited summaries (e.g., short reports, copies of viewgraphs, graphs, tables, etc.) can be obtained from the Project Officer.

B. Egan: The CTMD Program

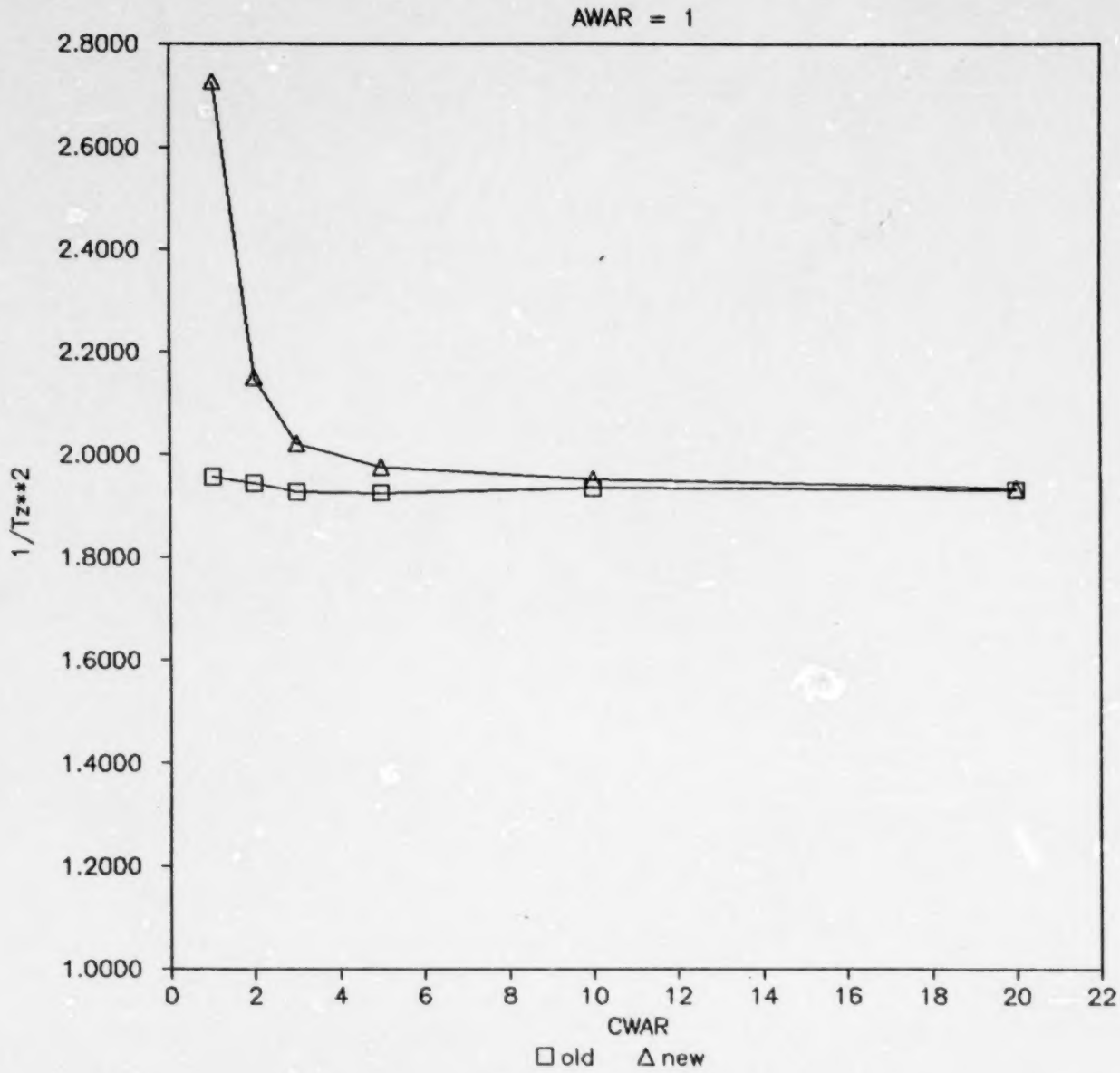
Bruce Egan presented the historical background of the CTMD program and the foundation upon which this phase of the program is based. He then summarized the CCB, HBR and Tracy tracer and flow visualization experiments. Finally, the major products of the CTMD were summarized. See the five Milestone Reports and the report by Hovind et al (1979) for more information.

T. Lavery: Model Development Goals

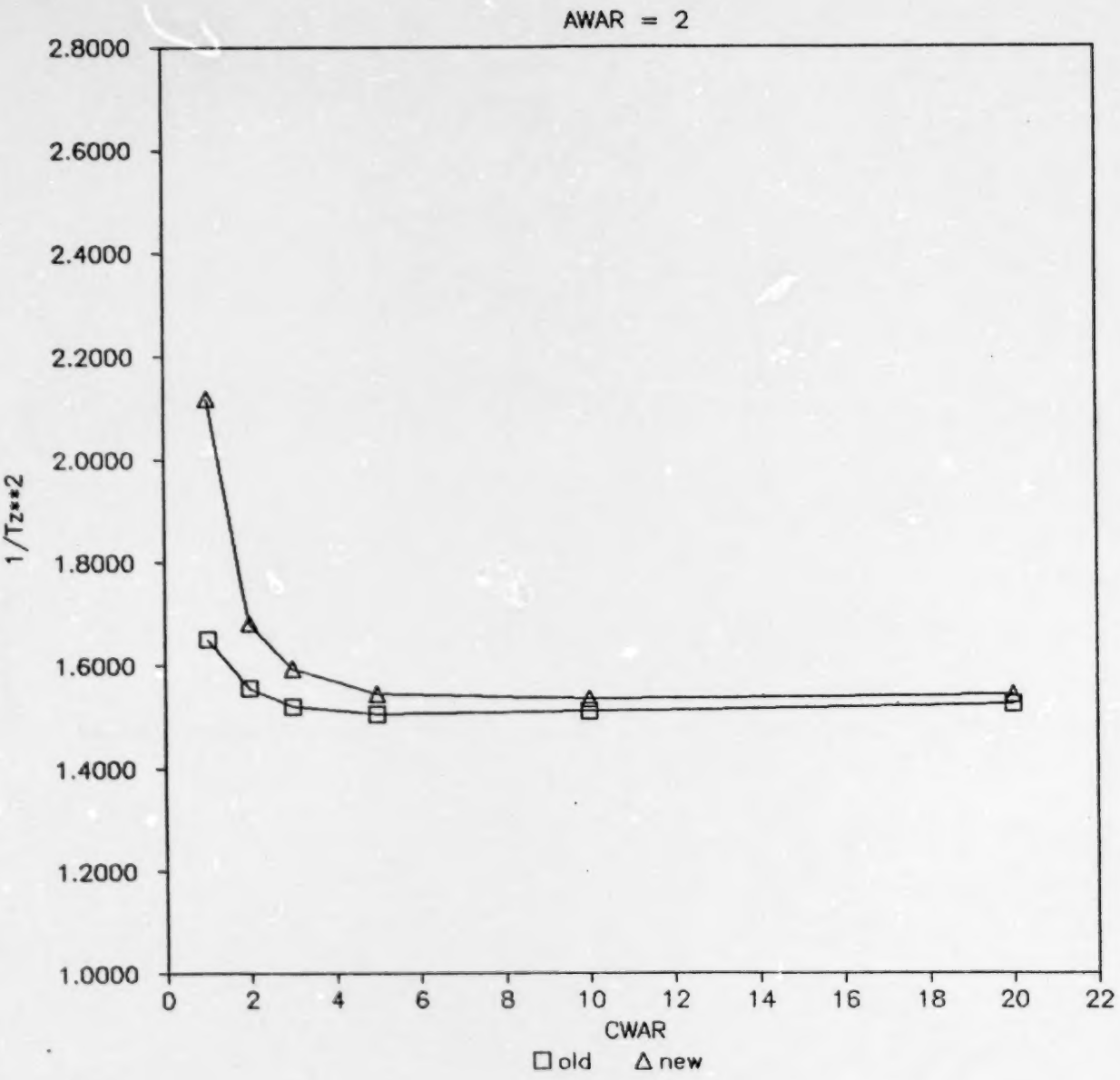
Thomas Lavery discussed the objectives of the CTMD project and solicited information from the workshop participants on how the objectives can ultimately be met. See the paper by Holzworth (1980) for a discussion of the objectives of the CTMD project.

D. Strimaitis: The Complex Terrain Dispersion Model

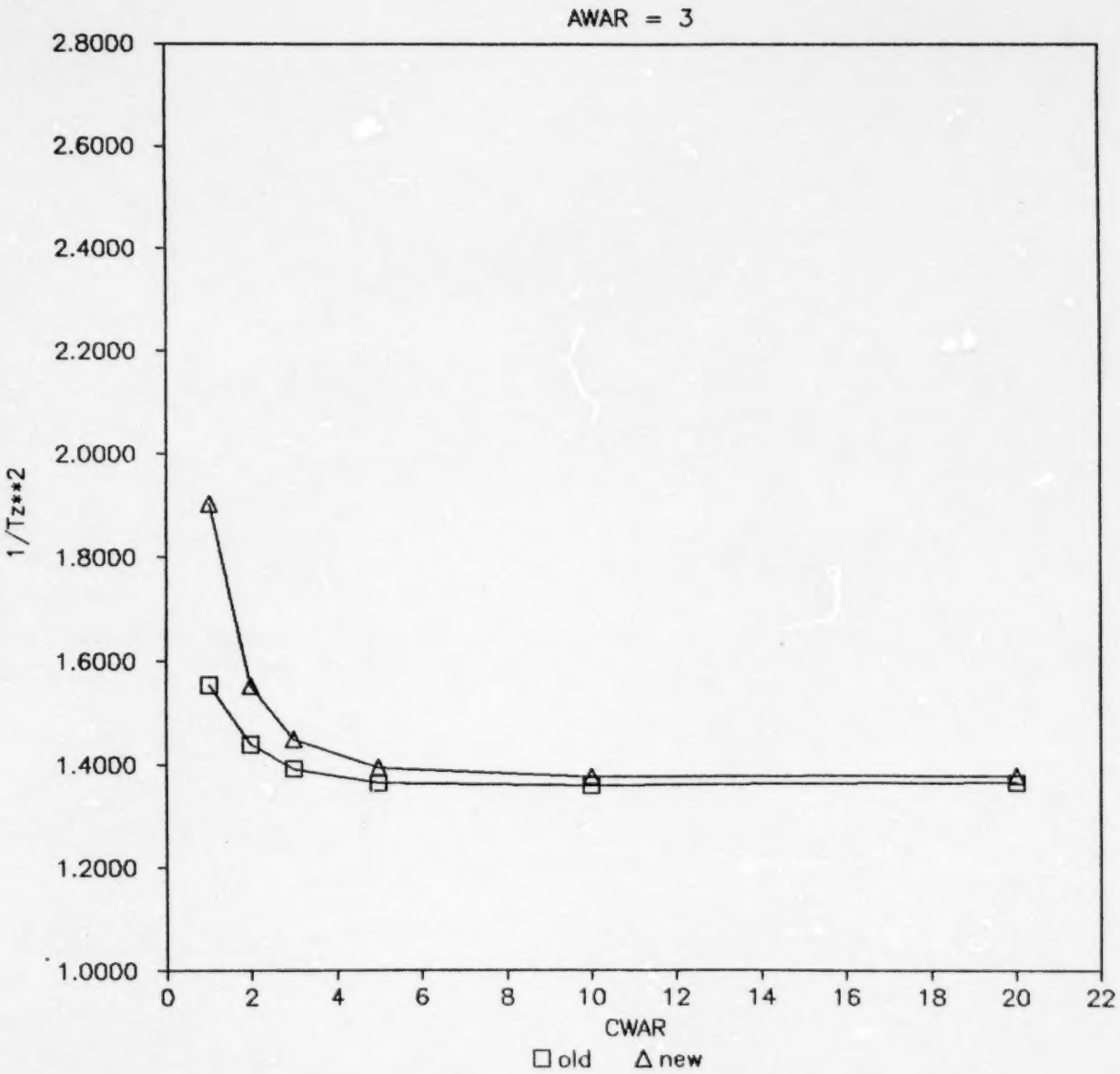
David Strimaitis presented an overview of CTDM, its essential features and how it is different from other Gaussian plume models. The material he presented is covered in the CTDM User's Guide (Strimaitis et al, 1985) that was given to the workshop participants. He also discussed the further development of the T-factors in CTDM. Specifically, more analyses and calculations were performed to investigate the differences between the way CTDM is presently calculating the T_z factor, and a way that is consistent with the Hunt and Mulhearn (1973) results. The calculations have been done for a source far enough upwind of the hill that the travel time to the upwind base of the hill is greater than the Lagrangian time scale for vertical diffusion. Typical results are shown in the three figures for example cases when the plume centerline is at one half the hill height.



D. Strimaitis, Figure 1



D. Strimaitis, Figure 2



D. Strimaitis, Figure 3

In these figures, AWAR is the along-wind aspect ratio of an ellipsoid, and CWAR is the cross-wind aspect ratio. The "old" data points identify T_z values as calculated by CTDM, whereas the "new" data points identify the results obtained with the Hunt and Mulhearn approach. Differences between the two results increase with increases in the rate of strain induced by the hill, being most dissimilar for the "spherical" hill (AWAR = CWAR = 1). Note that these computations make use of the net strain in the flow between the plume centerline (one half the hill height) and the surface for the special case of potential flow. We expect greater differences in the T_z values for streamlines nearer the surface, and also for an incident flow field with non-zero wind speed shear and stratification.

A. Venkatram: Diffusion in the stable boundary layer; and simplification of CTDM equations for semi-empirical modeling

Akula Venkatram reviewed the basic concepts of dispersion in the stable boundary layer. He discussed CTDM and how it could be simplified and still account for the principal effects of complex terrain on GLC. He then presented results of the application of the simplified model to a subset of the HBR CF_3Br dataset.

The simplified model is based on

$$C_h\ (X,0,0) = \frac{Q}{\pi u_f \sigma_{zf} \sigma_{yf}} \exp\ -\frac{1}{2}\left(\frac{H_s T_{hz}}{\sigma_{zf}}\right)^2 ,$$

where $T_{hz} = T_r/(1-R^2(1-T_r^2))^{1/2}$,

$R = \sigma_{zf}\ (X_o)/\sigma_{zf}(X)$,

X_o = distance at which H_c intersects the hill,

X = distance along hill, and f means flat terrain values.

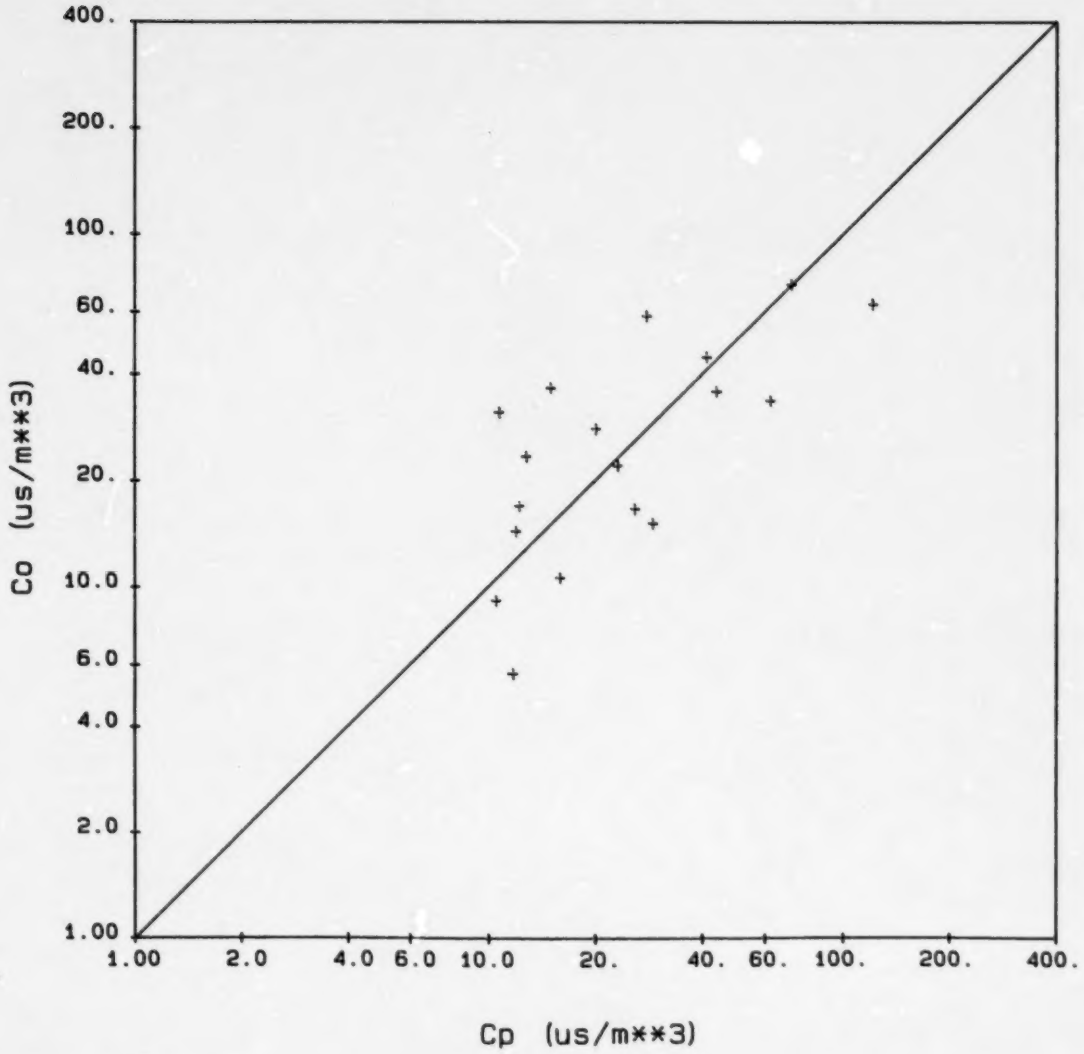
This simplied model was run using subsets of the HBR and CCB data bases. The results are shown in the following seven figures, which are scatter plots of observed versus predicted concentrations. For these runs a PDF version was utilized and T_r = Ø.4.

W. Snyder: Comparison of CTDM calculations with fluid modeling observations

The objective of William Snyder's analyses was to exercise the CTDM model and to compare its predictions with laboratory measurements of flow

PREDICTED VS OBSERVED MAXIMUM CONCENTRATIONS AT HBR
WHEN THE MAXIMUM OBSERVED CONCENTRATIONS LIE ABOVE HC

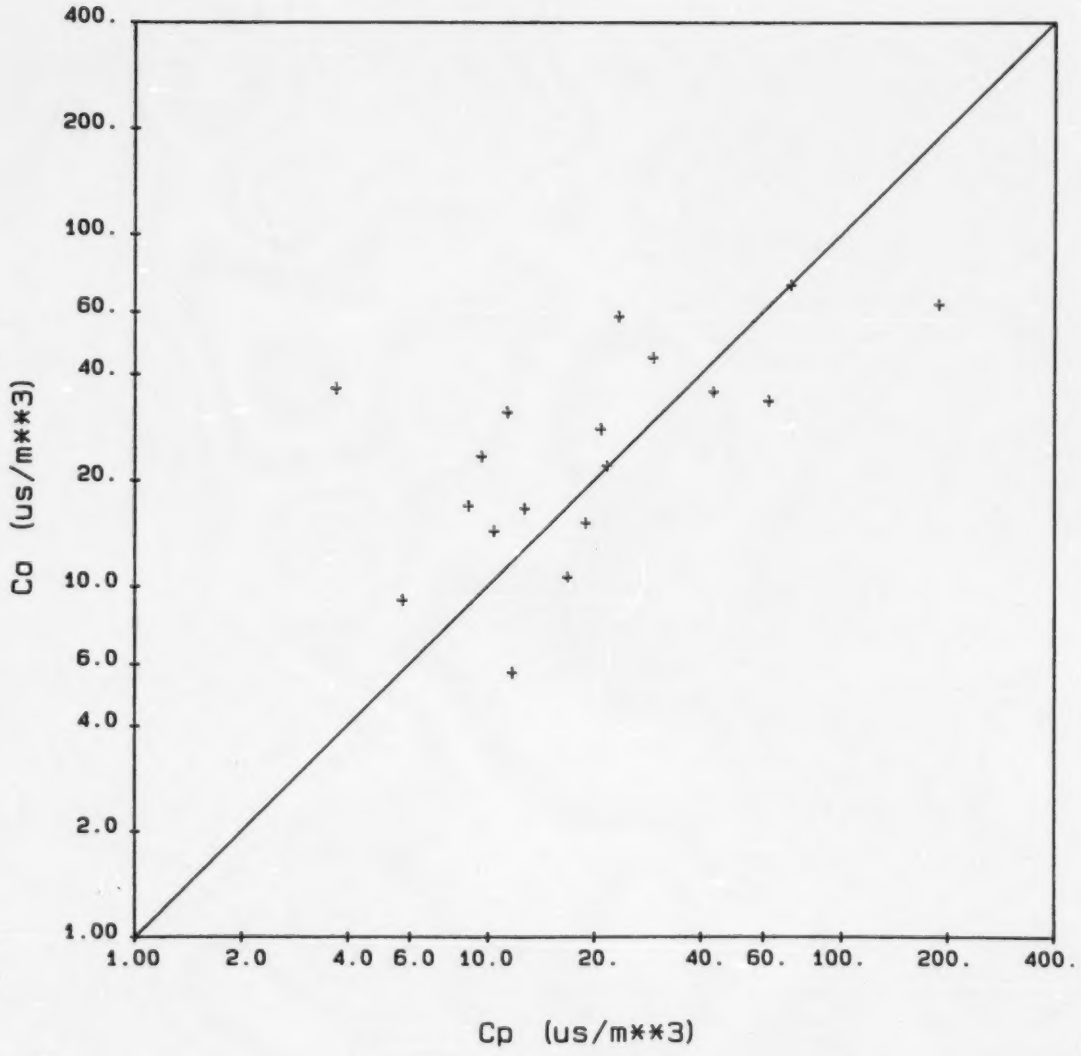
RECEPTOR ANGLE PDF



A. Venkatram, Figure 1

PREDICTED VS OBSERVED MAXIMUM CONCENTRATIONS AT HBR
WHEN THE MAXIMUM OBSERVED CONCENTRATIONS LIE ABOVE HC

STAGNATION ANGLE PDF



A. Venkatram, Figure 2

PREDICTED VS OBSERVED MAXIMUM CONCENTRATIONS AT HBR
WHEN THE MAXIMUM OBSERVED CONCENTRATIONS LIE BELOW HC

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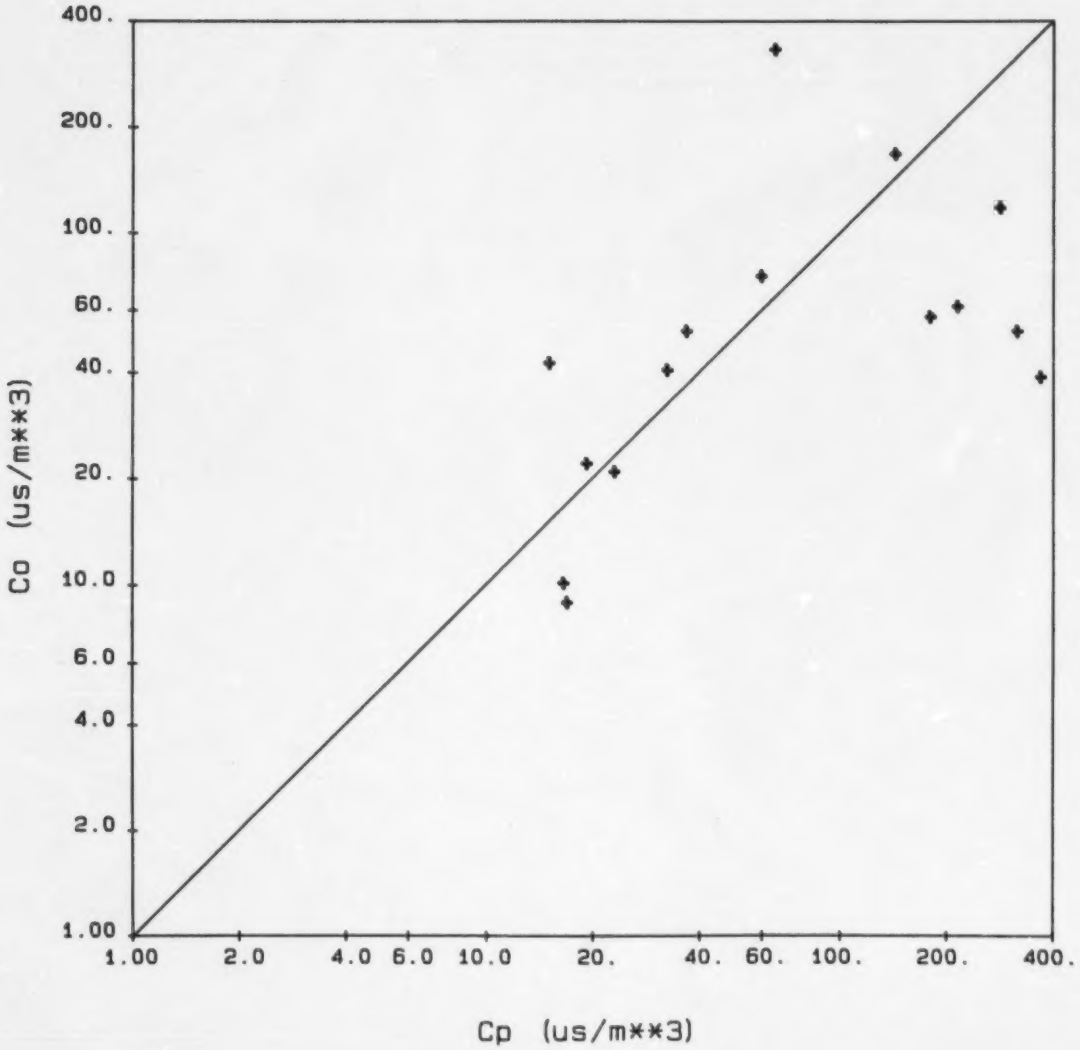

A. Venkatram, Figure 3

PREDICTED VS OBSERVED MAXIMUM CONCENTRATIONS AT HBR
WHEN THE MAXIMUM OBSERVED CONCENTRATIONS LIE BELOW HC

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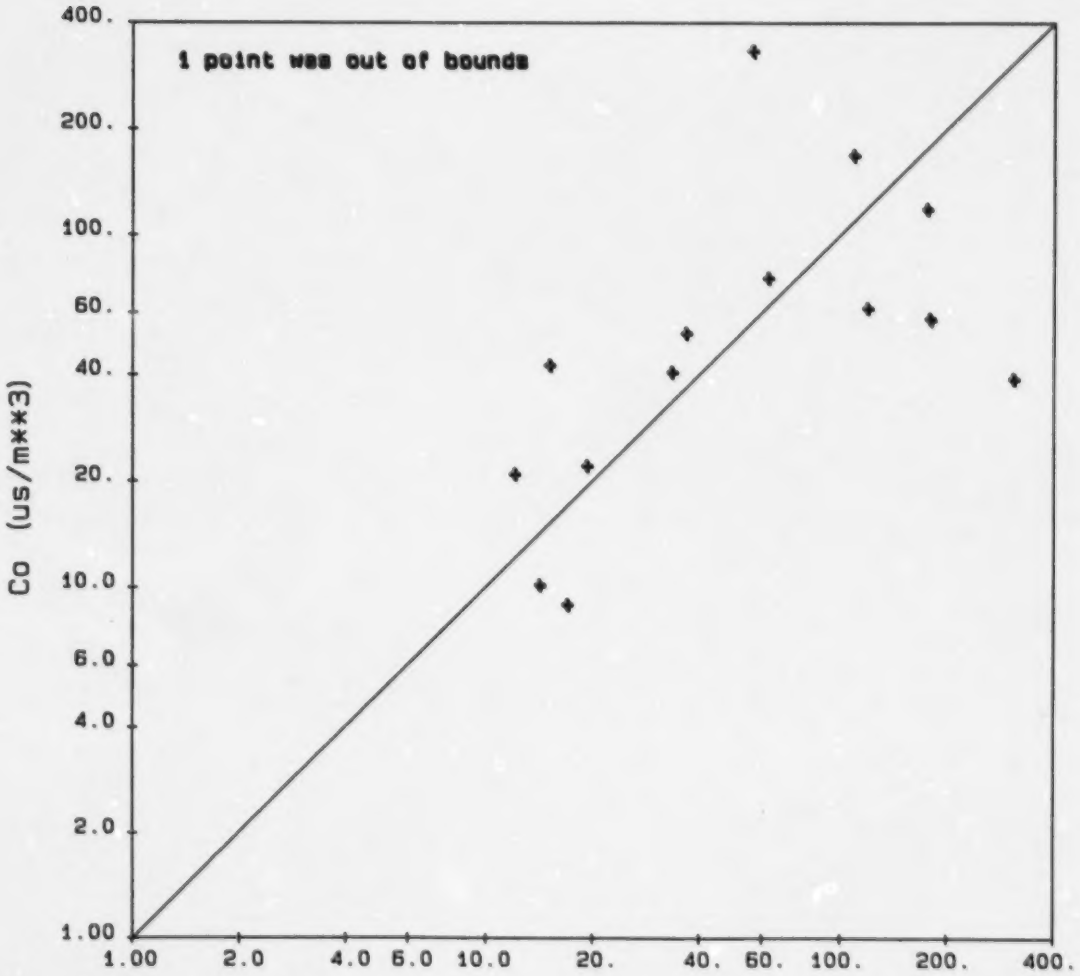
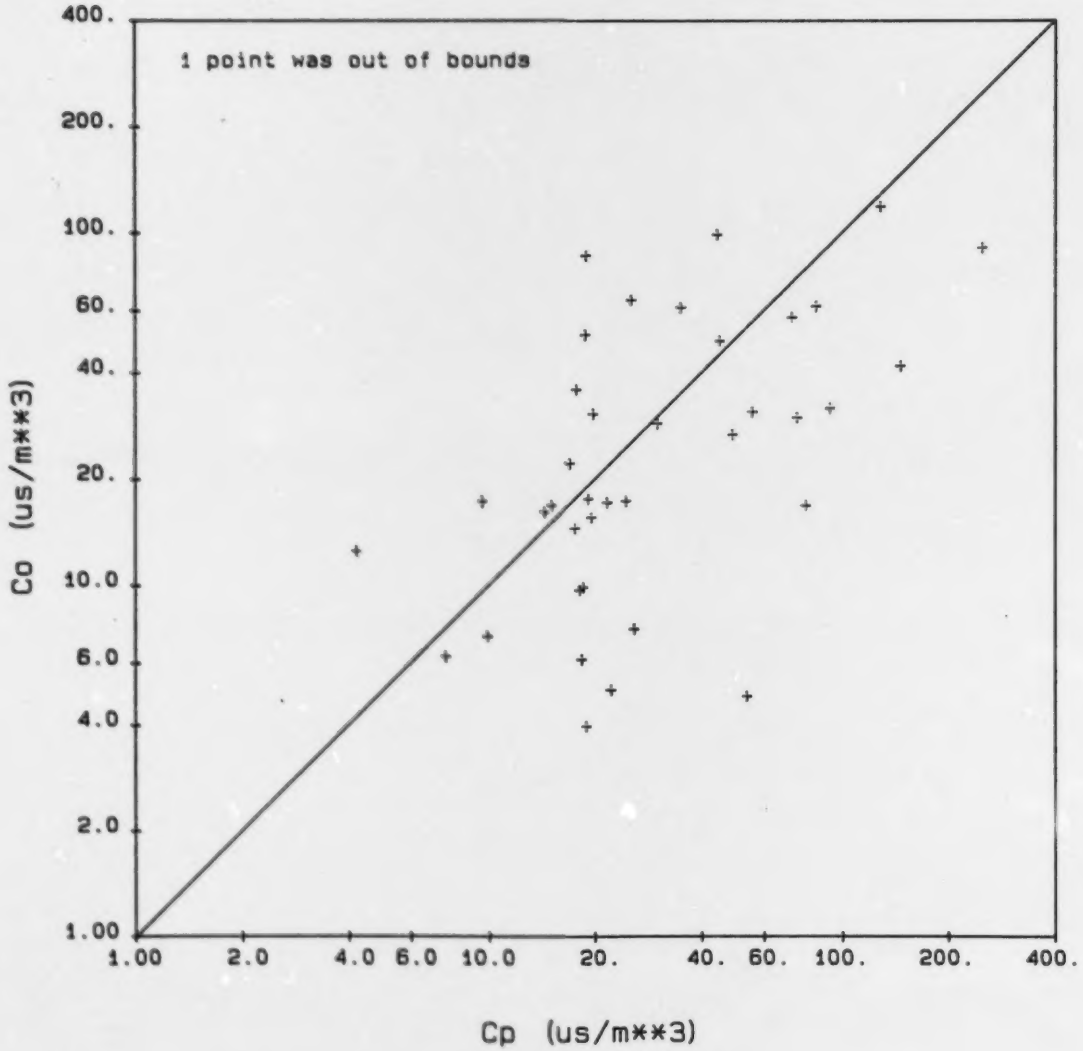


A. Venkatram, Figure 4

PREDICTED VS OBSERVED MAXIMUM CONCENTRATIONS AT CCB
WHEN THE MAXIMUM OBSERVED CONCENTRATIONS LIE ABOVE HC

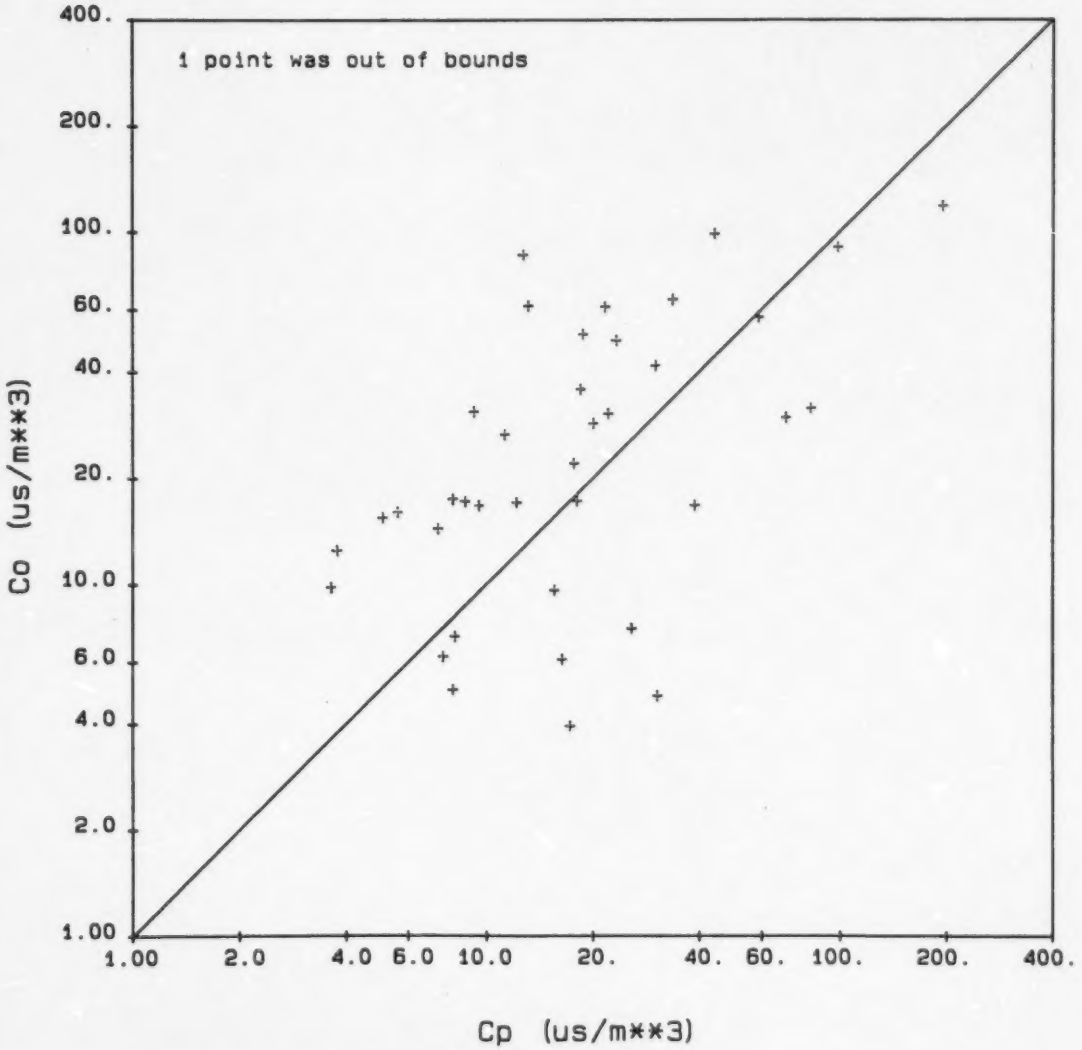
RECEPTOR ANGLE PDF



A. Venkatram, Figure 4

PREDICTED VS OBSERVED MAXIMUM CONCENTRATIONS AT CCB
WHEN THE MAXIMUM OBSERVED CONCENTRATIONS LIE ABOVE HC

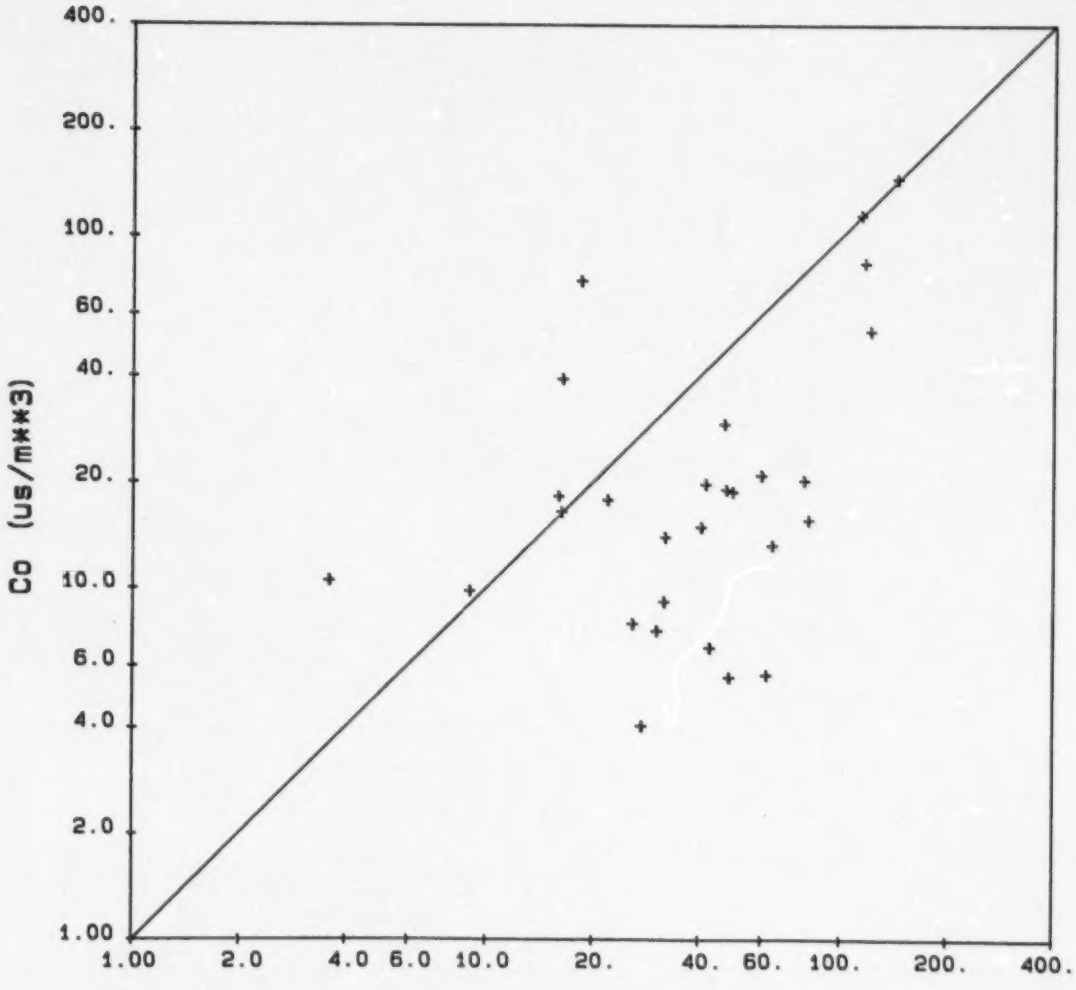
STAGNATION ANGLE PDF



A. Venkatram, Figure 5

PREDICTED VS OBSERVED MAXIMUM CONCENTRATIONS AT CCB
WHEN THE MAXIMUM OBSERVED CONCENTRATIONS LIE BELOW HC

RECEPTOR ANGLE PDF



A. Venkatram, Figure 6

and diffusion over hills made in the Fluid Modeling Facility. This was accomplished in four phases. In phase 1, CTDM calculations were compared with wind tunnel simulations of plumes released upwind of two- and three-dimensional hills in a neutral atmospheric boundary layer. Terrain amplification factors were compared for a matrix of source locations upwind of the hills. This phase was intended to test the LIFT module of CTDM, where the stratification was neutral and the potential flow calculations of LIFT should be most applicable. In phase 2, CTDM calculations were compared with stably stratified towing-tank observations, where plumes were released above the dividing-streamline height upwind of a three-dimensional hill. This phase was intended to again test the LIFT module, but this time under strongly stratified conditions. In phase 3, CTDM calculations were compared with strongly stratified towing-tank observations wherein plumes were released below the dividing-streamline height upwind of the Cinder Cone Butte model. This phase was intended to test the WRAP module exclusively. In phase 4, CTDM calculations were made for one selected hour of field conditions, and were compared with results of towing-tank observations. This phase was intended to exercise both the LIFT and WRAP modules of CTDM. The following excerpt from Snyder's report summarizes his conclusions.

The results of the analyses suggest:

1. From the neutral flow simulations (phase 1), it appears the hill effects are much too small, at least in comparison with wind tunnel results. Possible reasons include: (1) the plume trajectories may be too far from the hill surface; and (2) the potential flow calculations may not be handling the deep boundary-layer flow approaching the hill. The calculations (the TAF's) appear not to be too sensitive to the plume shape. A more likely possibility is that the plume centerline does approach the hill surface closely enough, but the plume is not mixed to the surface through the hill-surface boundary layer.

2. The present version of CTDM has a problem if the source is downwind of the upstream skirt of the hill.

3. From the stable flow simulations with releases above the dividing-streamline height (phase 2), it appears that the plume trajectories are again too far from the hill surface. Vertical deflections of streamlines appear to be strongly overestimated and lateral deflections appear to be strongly underestimated. In the towing tank, plumes released slightly above the dividing-streamline height spread broadly but thinly to cover the entire hill surface above the dividing-streamline height, whereas the CTDM plume is apparently deformed only slightly - it "hangs

together" in going over the top of the hill. A shortcoming of LIFT is its lack of an appropriate treatment of the stratification of effects in the flow that goes over the hill, i.e., streamline (hence plume) deformations at Fr=1 are treated the same as those at Fr=∞.

4. From the stable flow simulations with releases below the dividing-streamline height (phase 3), the WRAP module can give some poor results unless the input parameters (primarily σ_v) are within a fairly closely restricted range. WRAP cannot handle narrow plumes.

5. From the Case 206 simulations (phase 4), CTDM appears to do a reasonable job of predicting the values of the highest concentrations. Improvements in predictions from the 12/5-minute mode over the 1-hour mode appear to be small, at least in terms of calculating the highest concentrations, and would not appear to be justified on the basis of the additional computation costs.

The results of Snyder's analyses are presented in a detailed report (Snyder 1986).

W. Eberhard: The CTDM lidar data base; evaluation of σ_z formula using the BAO data base

Wynn Eberhard presented an overview of the lidar - - its operation, data products and data archive. He then presented monostatic sodar and lidar data from the Tracy data base for the period 8/12/84 0200-0300. He showed that sodar data can be used to identify elevated stable layers that could trap a plume and limit its vertical growth. He then presented some lidar estimates of vertical plume growth from the Stable Plume Experiment (SPEX) conducted at the BAO. CTDM estimates of σ_z were compared to lidar estimates. The CTDM values are underestimates of the observations, a result opposite to our experience with the Tracy data base. However, these results are considered preliminary.

R. McNider: Evaluation and Critique of CTDM

Richard McNider compared solutions from a dynamic flow and dispersion model with features of CTDM:

- terrain adjustment factors,
- neglect of local drainage flows, and
- dividing-streamline height (H_c).

He concluded that the numerical model simulations of H_c were consistent with CTDM. He pointed out that although it is beyond the scope of this phase of the CTDM, there are situations when local drainage flows are important in influencing GLC. The model user should be aware of this. The analysis of the terrain adjustment factors was inconsequential.

R. Paine: Results of CTDM Test Runs on Case Study Hills: Qualitative Comparisons

Robert Paine performed a series of CTDM sensitivity studies to ascertain the important input variables. He then compared results from tow tank experiments with CTDM simulations. He concluded that the model calculations are especially sensitive to the height of the plume relative to H_c and to the wind direction. His evaluation of the fluid model simulations suggests that the LIFT-WRAP transition component of CTDM could use some improvement.

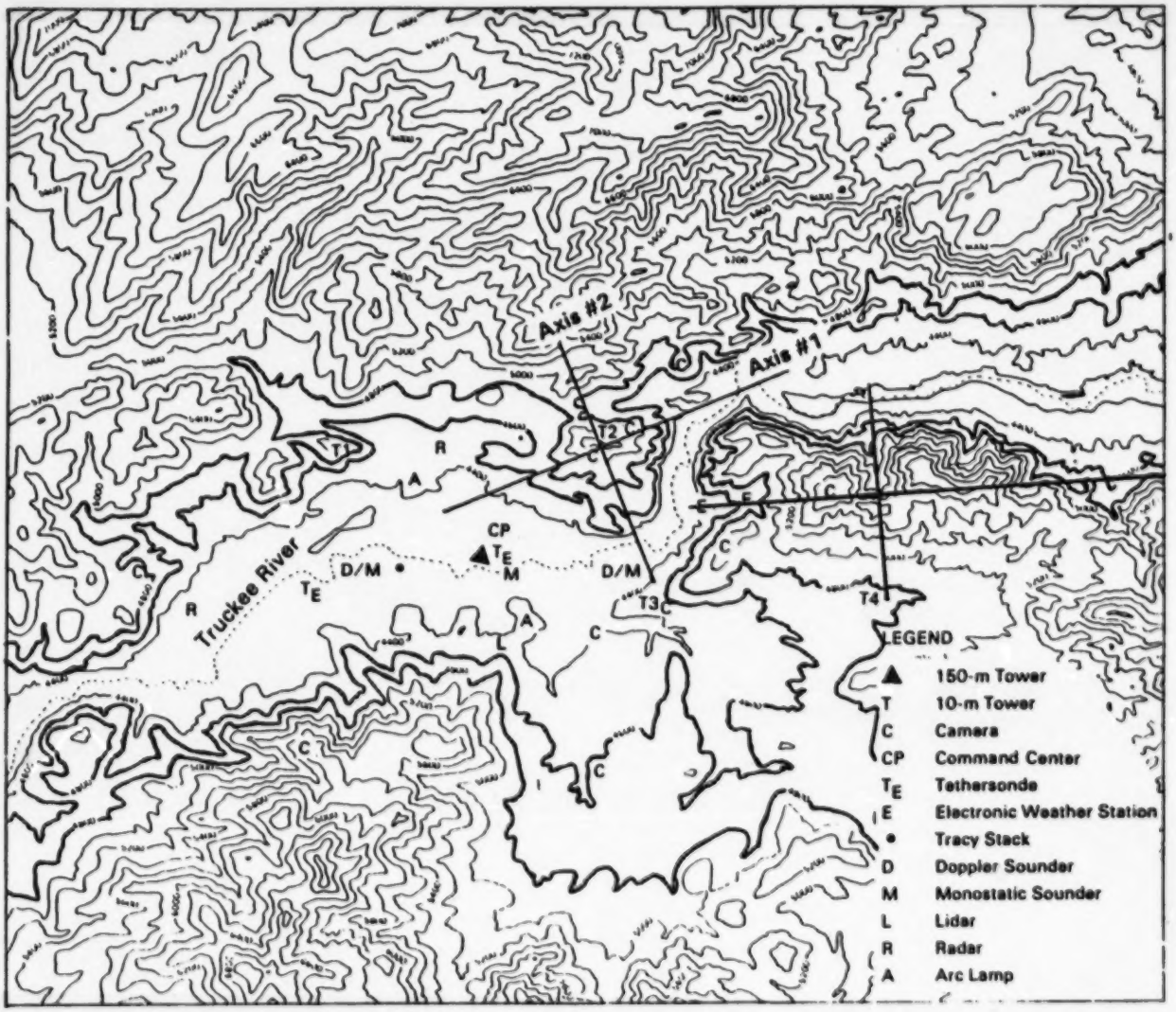
D. DiCristofaro: Evaluation of CTDM Using the FSPS MDA

The initial version of the FSPS MDA was used to run CTDM (Version 27485) for the Beacon Hill and Target Mountain sites. Lidar-derived plume heights were available for a total of 84 hours. CTDM was run for each of these hours and for each terrain site. Statistics were calculated only for those hours when the wind direction was towards the modeling site.

A description of the terrain inputs for Beacon Hill may be found in the CTDM User's Guide. The method used to describe the Target Mountain terrain inputs is discussed here. The layout of the FSPS experiment and the surrounding topography are shown in Figure 1. The heavy dark lines illustrate the major and minor axes of Target Mountain. For this initial modeling attempt, Target Mountain is modeled with only one terrain shape. Target Mountain may in fact be better modeled by using up to three separate terrain shapes.

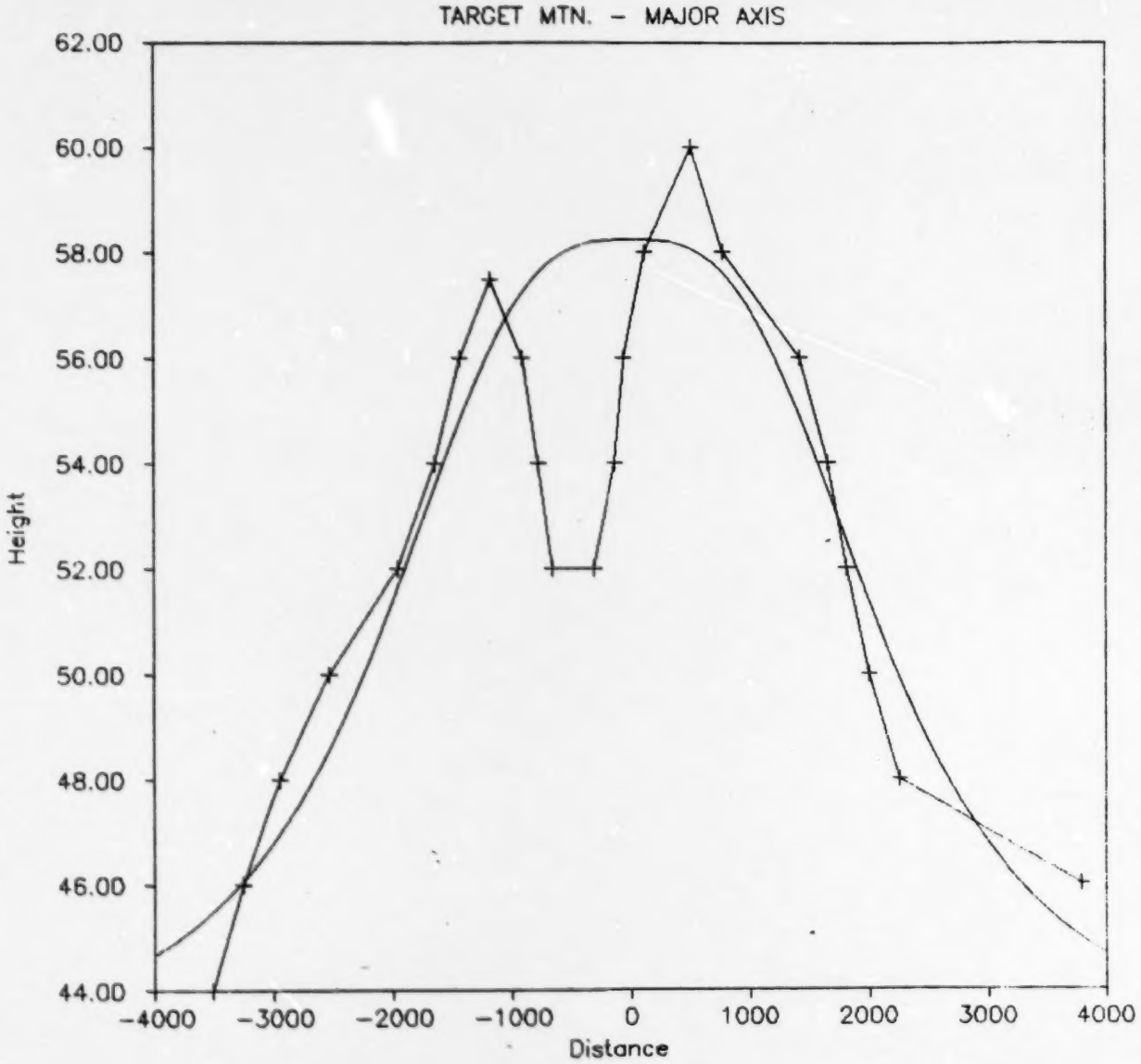
The actual Target Mountain terrain profile along the major axis is depicted in Figure 2 by the solid lines connected by plus symbols. The x-axis represents the distance from the hill center in meters, and the z-axis represents the contour elevations in thousands of feet. Presently, the model requires a symmetric hill to be input. Therefore, the actual terrain profile was averaged and this averaged profile is shown by the solid lines connected by boxes.

The major scale of the hill (L) is 2160 m and the relief height of the hill (H) is 475 m. Using this information plus the averaged terrain profile, a best fit analysis was performed to determine p, the exponent whose value is chosen to give an adequate representation of the hill shape



Terrain Effects

D. DiCristofaro, Figure 1



D. DiCristofaro, Figure 2

profile and h_o, the height of the zero-plane above grid zero. For the major axis, the exponent p is set to 3.1 with h_o set to Ø.

The modeled terrain profile is shown in Figure 3 by the solid line. The actual terrain shape is superimposed onto the plot. The modeled terrain profile seems to define the complex shape of Target Mountain adequately.

This same procedure was used to define the terrain profile of the minor axis. The actual terrain shape of the minor axis is shown in Figure 4 by the solid lines connected by plus symbols and the average profile is shown by the solid lines connected by boxes. The minor scale of the hill (L) is 75Ø m and p is estimated to be 1.7. The solid line in Figure 5 shows this modeled terrain profile and this may be compared with the actual profile, which is shown by the solid lines connected by plus symbols.

A total of 47 modeling hours were found to be applicable to the Target Mountain area. The mean (M_g) and standard deviation (S_g) of the peak residual (C_o/C_p) are:

$M_g = 1.3$

$S_g = 2.3$

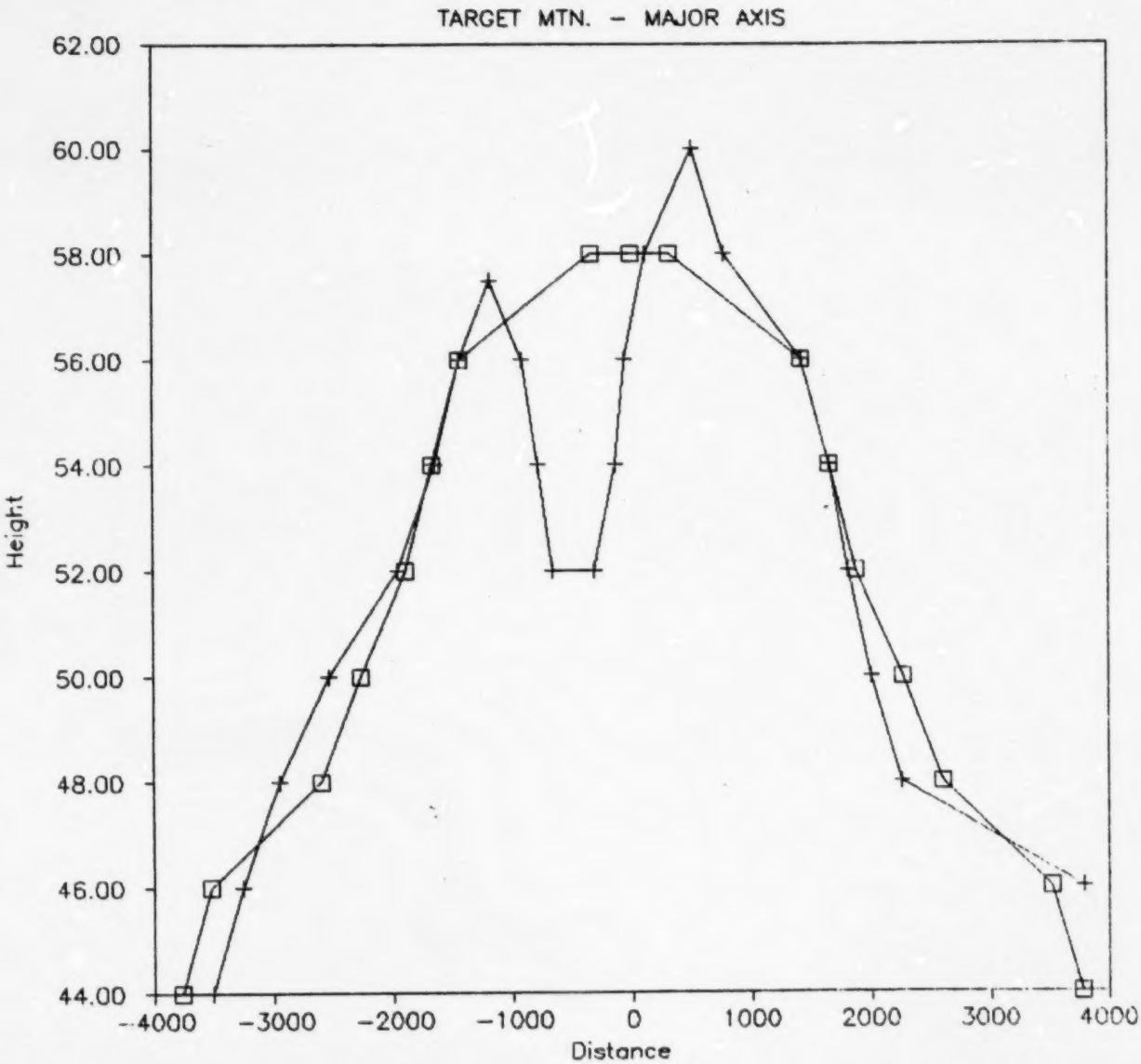
Thus, for the Target Mountain area, CTDM is underpredicting on average by 3Ø%.

The average top two residuals are plotted in Figure 6 as $\ln(C_o/C_p)$ versus $(Z_r-H_c)/H_c$. A Ø.69 on the y-axis represents a factor 2, 1.39 a factor of 4, etc. When Z_r is slightly less than or close in value to H_c, the model does poorly. This is an area where H_c must be estimated as accurately as possible, and the calculation of H_c for Target Mountain will have to be examined more closely. In Figure 7, $\ln(C_o/C_p)$ is plotted as a function of wind speed. The model does slightly worse under high wind speed conditions.

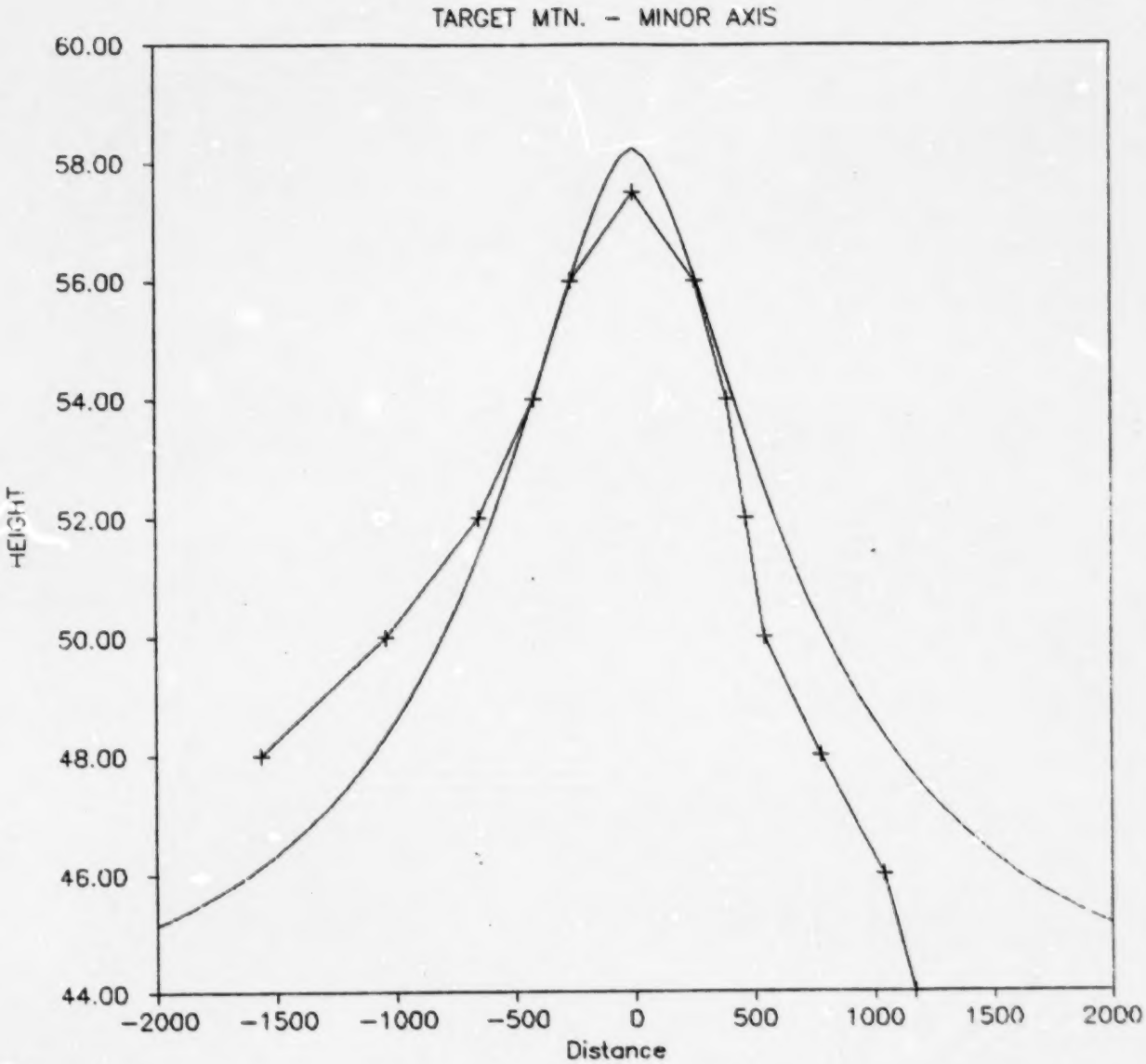
A total of 39 modeling hours were found to be applicable to the Beacon Hill area. The mean and standard deviation of the peak residuals (C_o/C_p) are:

$M_g = 1.2$

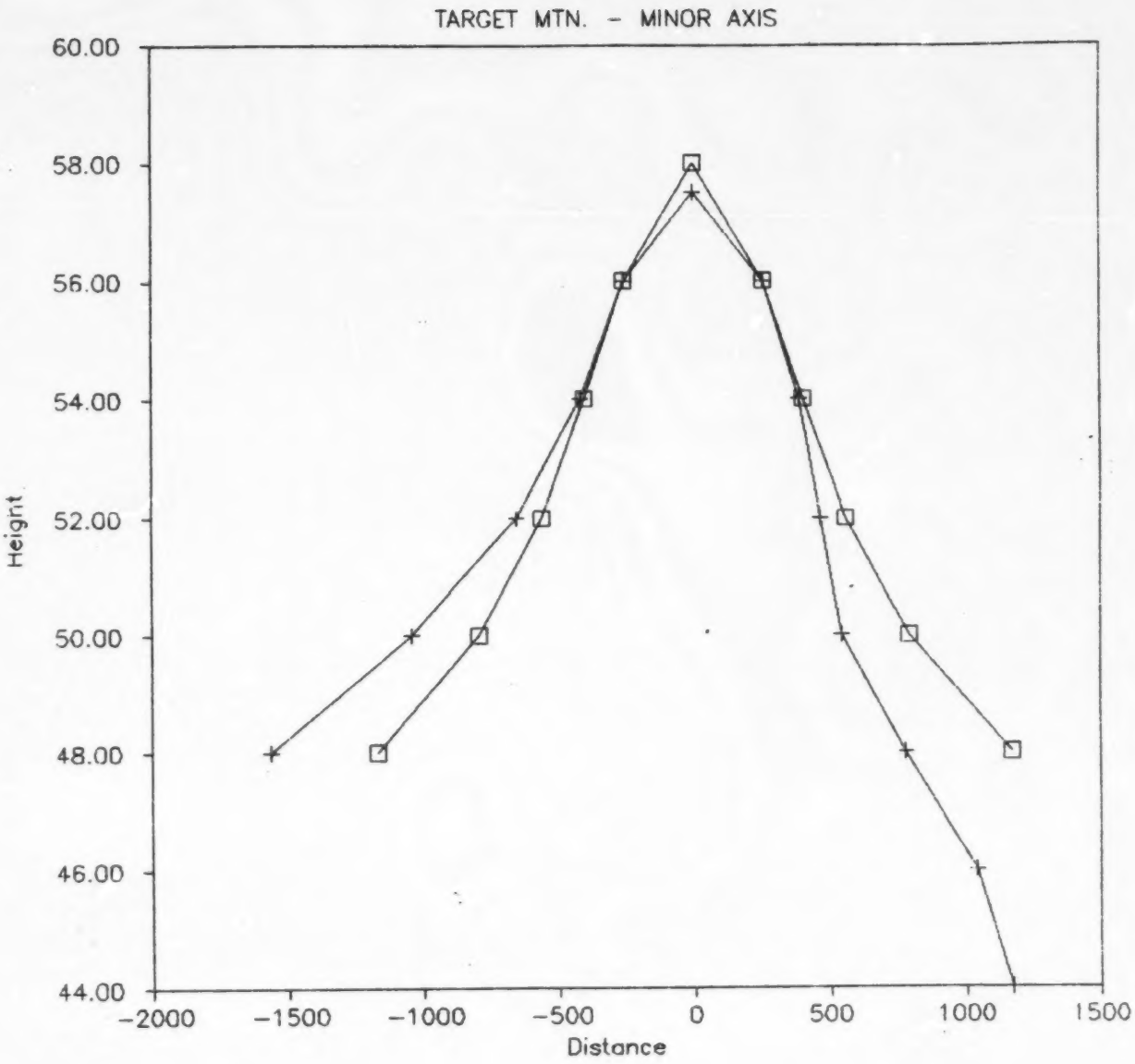
$S_g = 1.9$



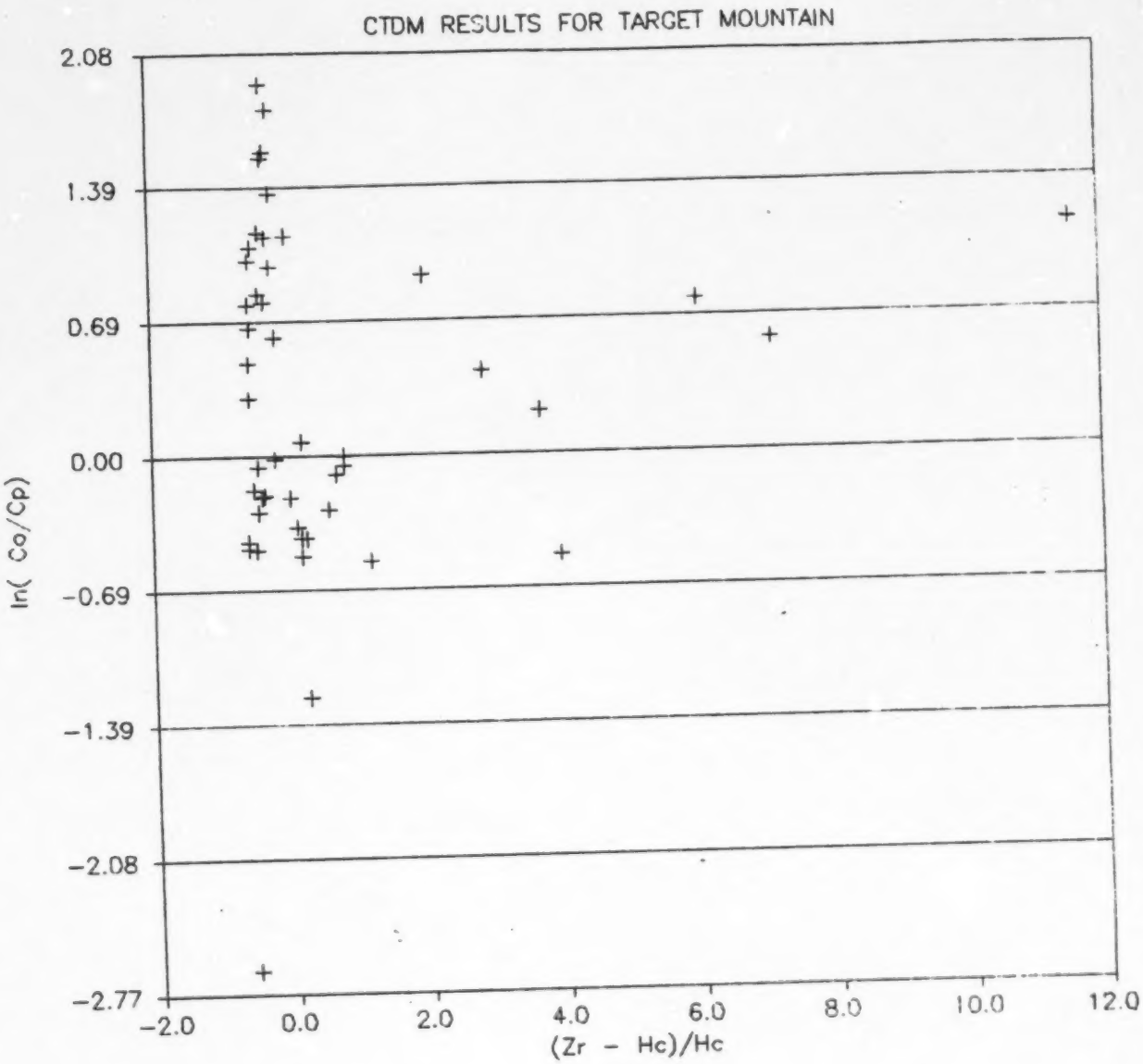
D. DiCristofaro, Figure 3



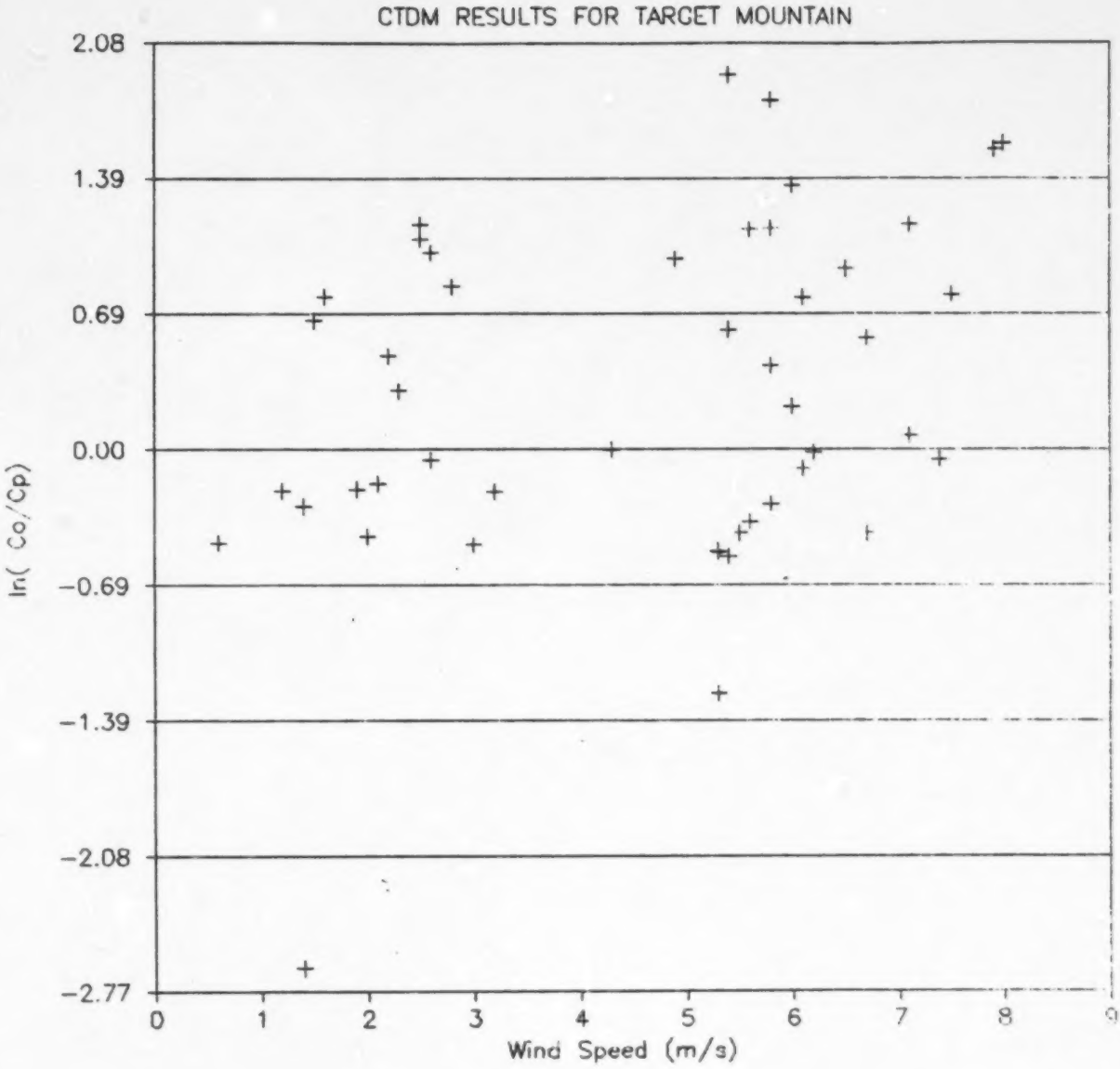
D. DiCristofaro, Figure 4



D. DiCristofaro, Figure 5



D. DiCristofaro, Figure 6



D. DiCristofaro, Figure 7

For the Beacon Hill site, CTDM is underpredicting on average by 20%.

In Figure 8 the average top two residuals [$\ln(C_o/C_p)$] are plotted against $(Z_r-H_c)/H_c$. 74% or 29 hours lie within a factor of two. As H_c becomes less than Z_r, the model does better. In Figure 9, $\ln(C_o/C_p)$ is plotted as a function of wind speed. The model tends to perform just as well under light winds as it does under high wind speeds.

M. Garrison: Sensitivity tests at Westvaco; model comparisons and sensitivity tests using the Warren data set

Mark Garrison ran CTDM and performed sensitivity studies for two sites: the Westvaco mill near Luke, Maryland and the Pennsylvania Electric Co. Warren Station in Pennsylvania. Both sites have very complicated terrain surrounding the stacks. He exercised CTDM for both sites and varied several of the input variables, e.g., terrain profile exponent, location of met tower, length scale for major axis, etc. He "derived" the meteorological input data from nearby tower data. Based on the model simulations and sensitivity analyses, he made several recommendations regarding: applying the model, transfer of technology, requirements for a regulatory model, etc.

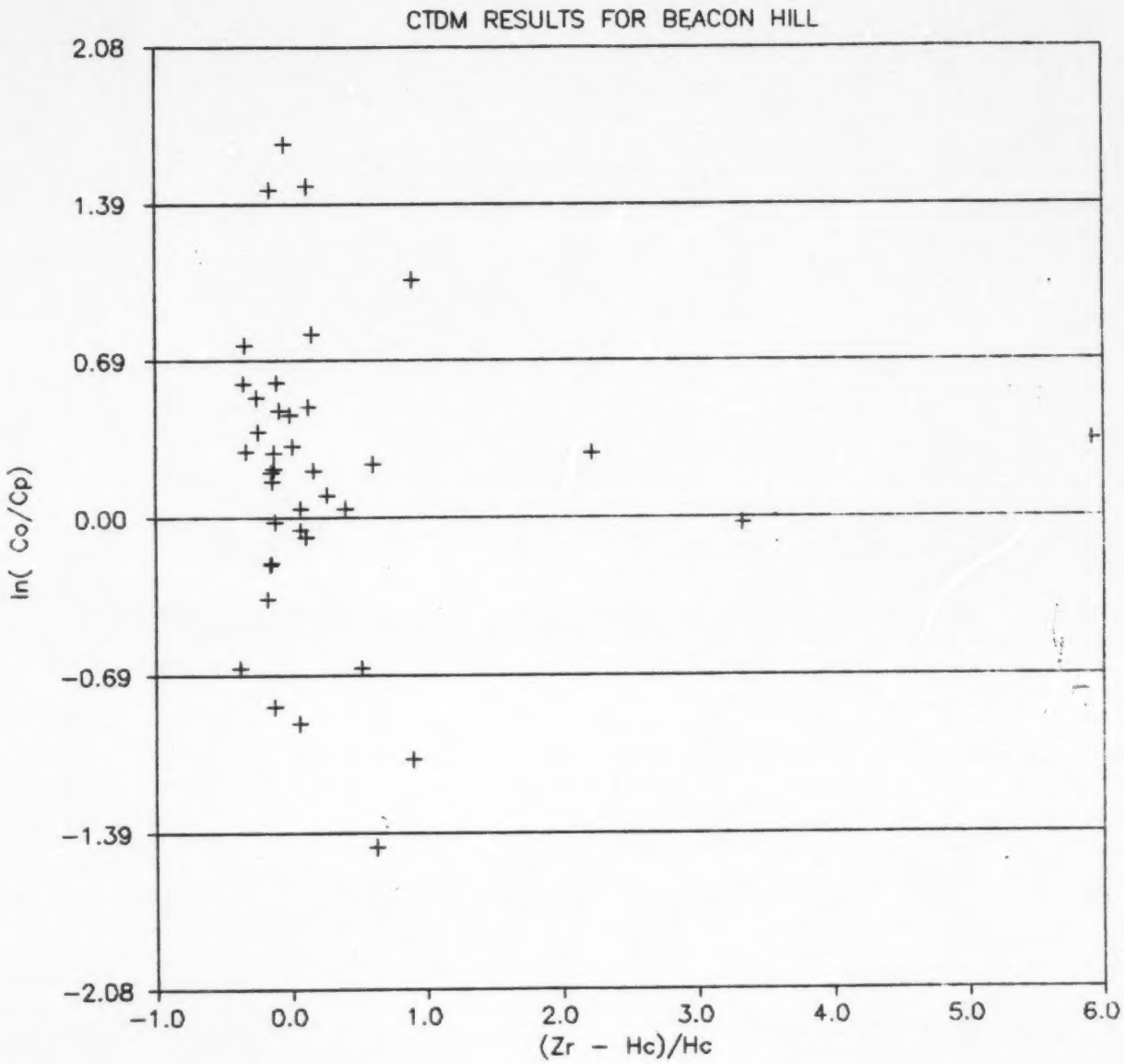
R. Lee: An evaluation of CTDM using the CCB and Westvaco data bases and a comparison with COMPLEX I

Russ Lee evaluated CTDM and COMPLEX I using an 80-hour subset of the CCB data base. His results demonstrated that CTDM performed better than COMPLEX I. The following figure shows scatter plots of predicted versus observed SF_6 concentrations for the CTDM and COMPLEX I simulations. The table shows a statistical analysis of the results.

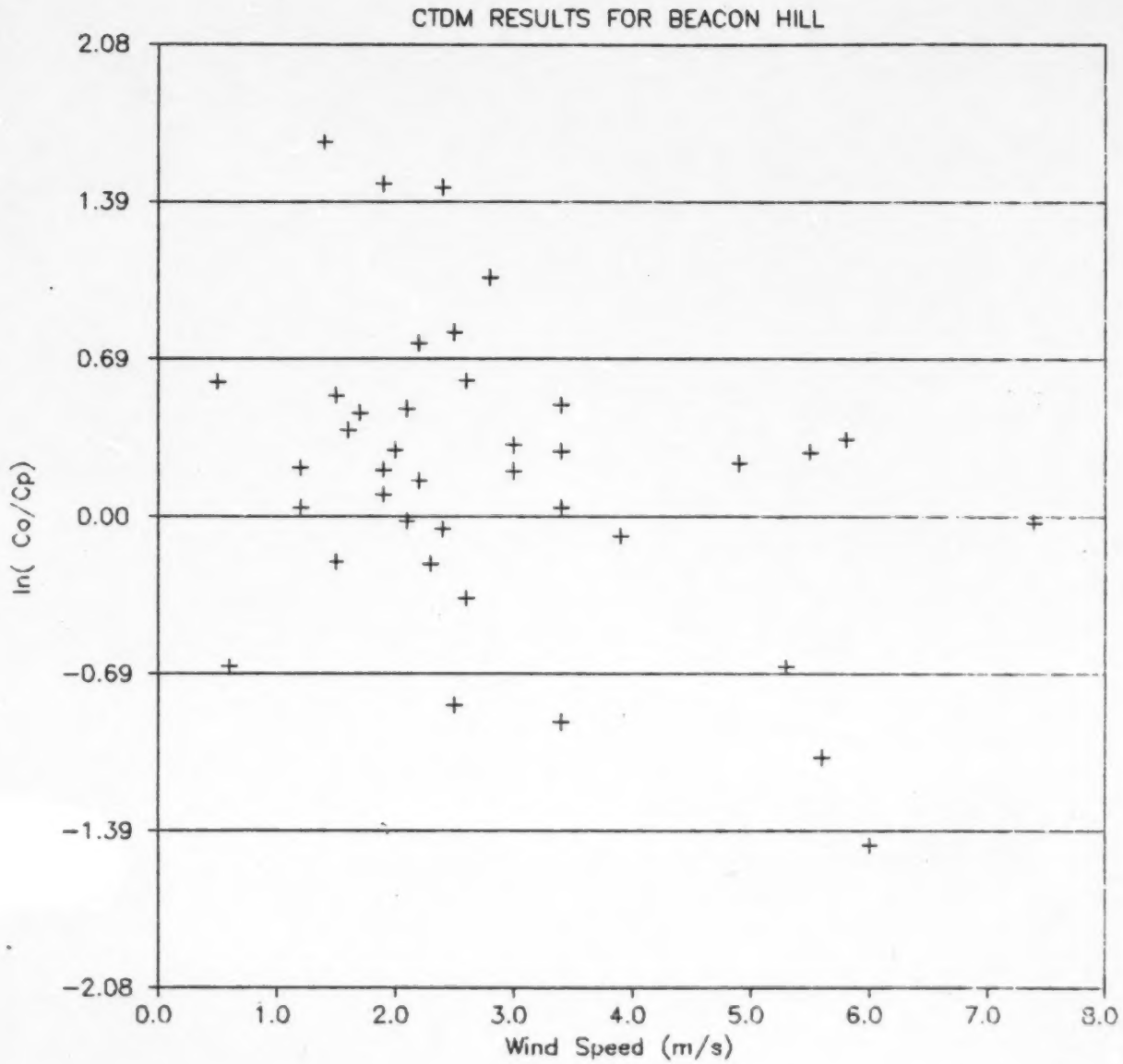
He then discussed the application of CTDM to the Westvaco site. He illustrated the difficulty and subjectivity in specifying terrain, in selecting meteorological data and other critical parameters. He recommended that the code include objective methods for selecting terrain and the user's guide contain specific recommendations on meteorological measurements and their location.

L. Sedefian: An evaluation of CTDM, COMPLEX I and NYSDEC models using the Roseton Station data base

Leon Sedefian presented the results of his evaluation of the three models. The data base was assembled from SO_2 measurements (two sites in high terrain), meteorological data (90-m tower and two 10-m towers at the SO_2 sites) and SO_2 emissions data provided by Central Hudson Gas & Electric

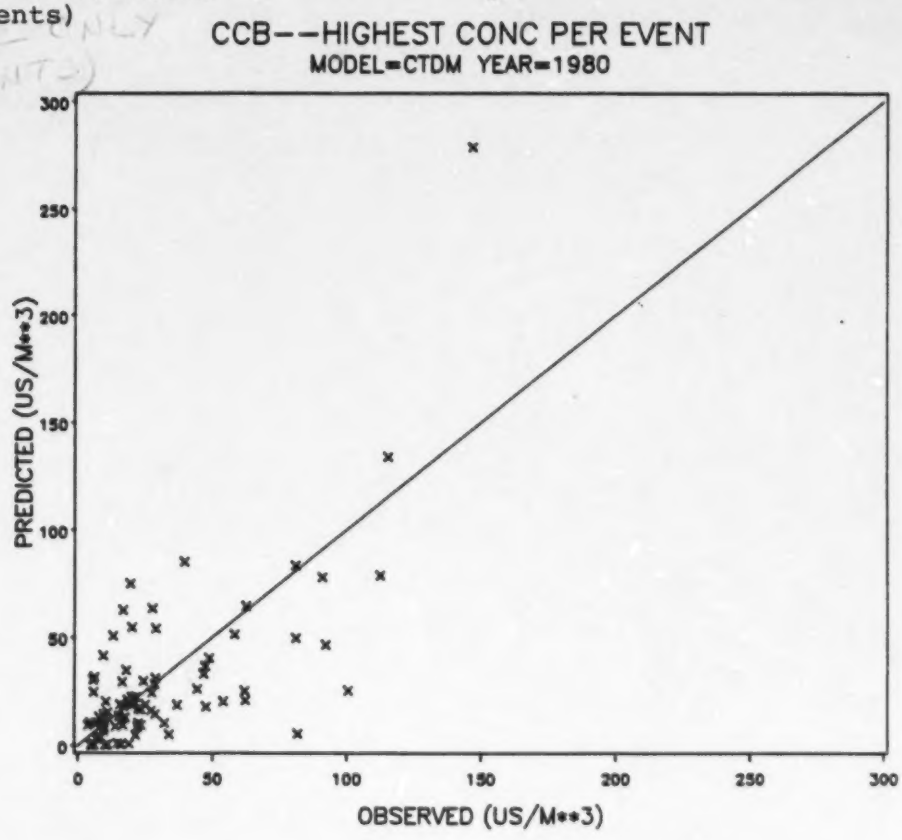


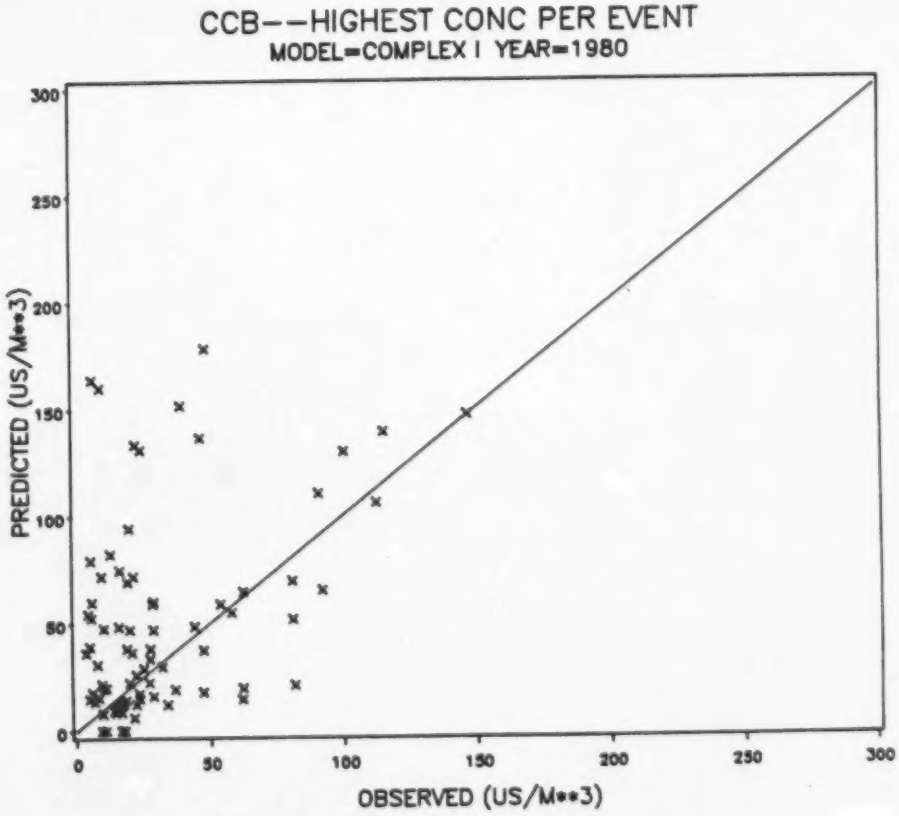
D. DiCristofaro, Figure 8



D. DiCristofaro, Figure 9

NOTE: PAIRED IN TIME ONLY
(80 Events)





R. Lee, Figure 1

R. Lee

Table 1

MODEL PERFORMANCE STATISTICS
ALL OBSERVED AND PREDICTED PAIRED IN TIME AND LOCATION
FOR VARIOUS DATA SETS
CINDER CONE BUTTE, 1980
SF6 CONCENTRATIONS (US/M3)

MODEL =COMPLEX I

DATA SET	NUMBER OF EVENTS	AVERAGE OBSERVED VALUE	AVERAGE DIFFERENCE	STANDARD DEVIATION OF RESIDUALS
ALL DATA	3124	6.8398	-6.543	22.7815
DIST<=900. H<16.	155	9.1243	-0.620	23.3067
DIST<=900. 16.<=H<=26.	279	7.2359	-8.972	29.0409
DIST<=900. H>26.	220	18.2705	-17.598	36.0708
DIST>900. H<16.	279	8.1914	-0.234	12.8974
DIST>900. 16.<=H<=26.	1489	6.5851	-5.837	23.0461
DIST>900. H>26.	702	2.5908	-7.028	13.7307
WIND SPEED < 2.5	1707	7.7725	-10.535	28.1180
2.5 <= WIND SPEED <= 5.0	870	6.3671	-2.759	14.3453
WIND SPEED > 5.0	547	4.6810	-0.042	6.7627
STABILITY = C,D	678	6.2655	-0.183	12.5303
STABILITY = E	659	6.5671	-0.994	12.4511
STABILITY = F	1787	7.1582	-11.003	27.2614

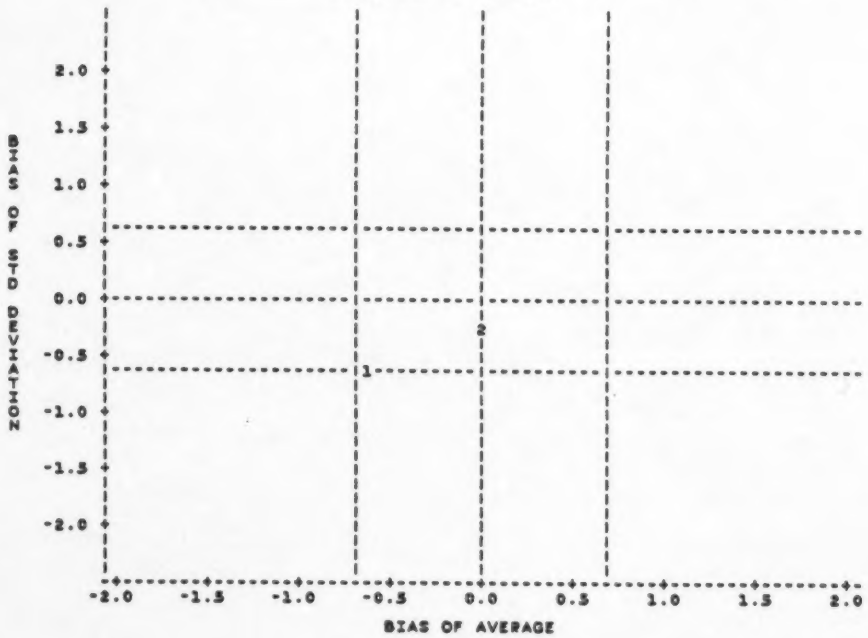
MODEL =CTDM

DATA SET	NUMBER OF EVENTS	AVERAGE OBSERVED VALUE	AVERAGE DIFFERENCE	STANDARD DEVIATION OF RESIDUALS
ALL DATA	3124	6.8398	-0.0125	14.4191
DIST<=900. H<16.	155	9.1243	5.2802	15.2354
DIST<=900. 16.<=H<=26.	279	7.2359	-2.6445	13.2907
DIST<=900. H>26.	220	18.2705	-5.7769	35.6152
DIST>900. H<16.	279	8.1914	1.7402	12.6889
DIST>900. 16.<=H<=26.	1489	6.5851	0.9659	10.5474
DIST>900. H>26.	702	2.5908	-1.1063	9.3319
WIND SPEED < 2.5	1707	7.7725	-1.8570	17.4898
2.5 <= WIND SPEED <= 5.0	870	6.3671	3.1319	10.1079
WIND SPEED > 5.0	547	4.6810	0.7428	6.6215
STABILITY = C,D	678	6.2655	0.7309	9.4888
STABILITY = E	659	6.5671	3.7854	10.7104
STABILITY = F	1787	7.1582	-1.6950	16.6971

SUMMARY TABLE

MODEL	NUMBER OF EVENTS	AVERAGE OBSERVED VALUE	AVERAGE DIFFERENCE	LOWER LIMIT	UPPER LIMIT	STANDARD DEV. OF RESIDUAL	LOWER LIMIT	UPPER LIMIT	ROOT MEAN SQ ERROR	AVERAGE ABSOLUTE RESIDUAL	PEARSON CORR. COEF.	VARIANCE COMPARISON	LOWER LIMIT
COMPLEX I	3124	6.83979	-6.5432	-7.3425	-5.7439	22.7815	22.2303	23.3609	23.6990	12.3772	0.333	0.296	0.276
CTDM	3124	6.83979	-0.0125	-0.3184	0.4934	14.4191	14.0702	14.7858	14.4167	6.5490	0.505	0.665	0.620

CINDER CONE BUTTE, 1980--ALL CONCENTRATIONS
1=COMPLEX I 2=CTDM



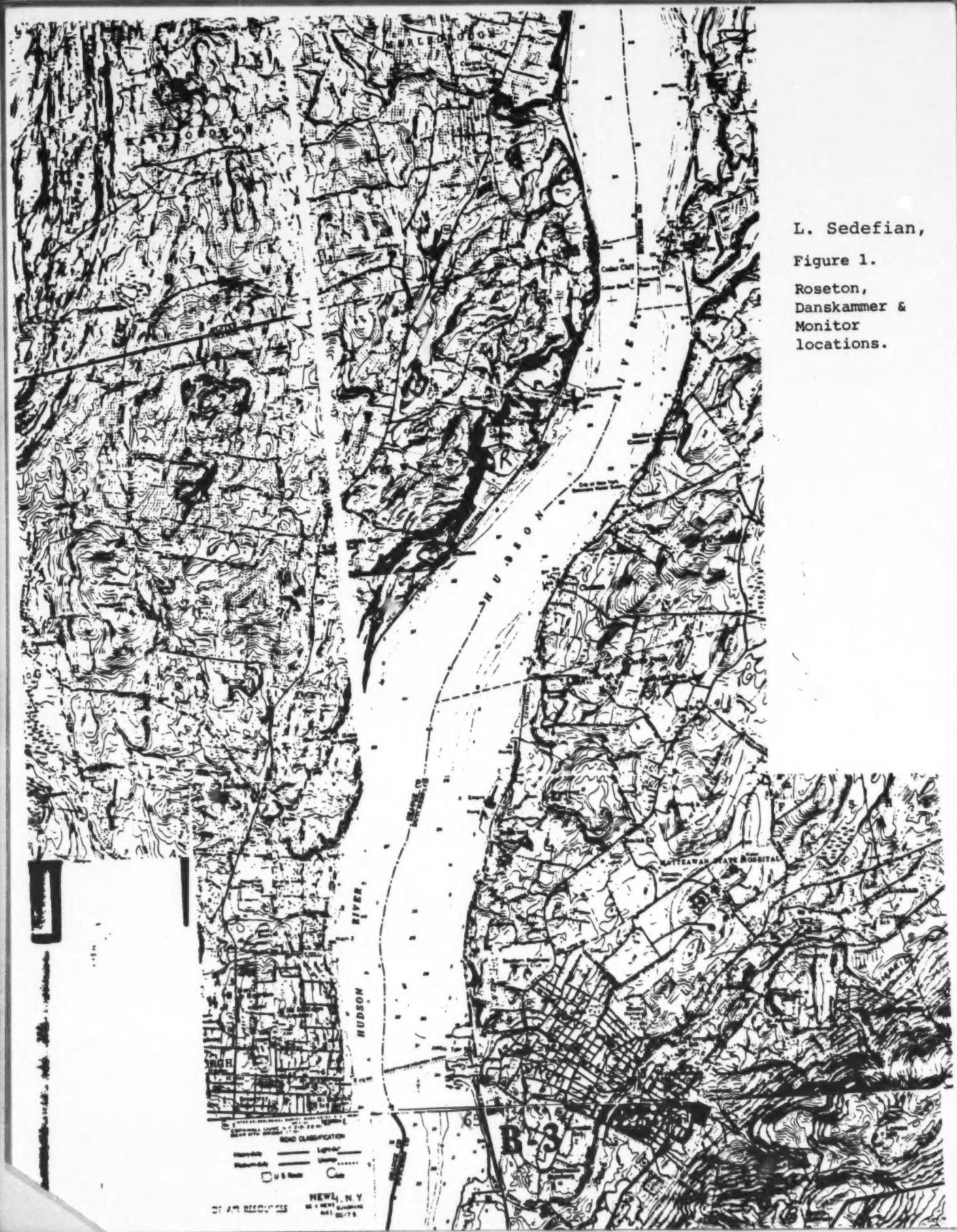
Co. from the Roseton Generating Station. The following figure shows the locations of the station and two monitors (Mt. Beacon - southeast of the plant and Marlboro - northwest of the plant). The two tables show comparisons between model calculations and observations. CTDM outperformed the other models substantially.

N. Bowne: Preliminary Tests of the EPA Complex Terrain Model

Norman Bowne prepared a report on operational evaluations of CTDM and limited sensitivity tests. He used a data base assembled from measurements collected around the Warren station in Pennsylvania. CTDM calculations were compared to SO_2 observations taken at six sites. Concentrations were overpredicted at all sites.

The Warren station is located along the Allegheny River near rural Warren, PA about 40 miles east of Erie, PA. The site terrain is forested and is quite rough with hills rising 150m above the river (Figure 1). The Warren station is coal fired and has a capacity of 90 MW. The stack height is 61 m and the typical plume rise during stable conditions is about 150 to 400 m. The terrain rises to the north of the station to a height of 216 m above the stack base, and this ridge contains six air quality monitoring sites at varying elevations and distances from the stack. A seventh monitoring site is located on elevated terrain on the south side of the river valley. In addition, there are three meteorological monitoring sites. One is located near the stack at Starbrick with the tower's top level approximately at the stack top elevation. A second site is located at the top of the ridge to the north at Yankee Bush, and the third site at Preston is approximately halfway in between the other two. For this evaluation only data collected at the first two sites have been used. Meteorological and SO_2 data for the one year period between December 1, 1984, and November 30, 1985, were utilized.

A small refinery is located to the east of the Warren station and emits about 1500 tons per year of SO_2. Winds in the sector from 135 degrees to 270 degrees are expected to carry the plume towards the ridge area and by selecting only periods when the indicated wind direction is in this sector the complicating impacts of the refinery are minimized. Table 1 presents a comparison of the observed and predicted concentrations for the entire data set. The paired in time and space correlation coefficients for each station are characteristically low and indicate little ability of the model to match hour by hour concentration patterns. The results are similar to the correlation coefficients found in previous PMV&D model evaluations. Significant overprediction of the mean concentration is also seen. This is contrary to the results of previous PMV&D evaluations, in which the mean concentration was generally underpredicted. The reason for this result is



L. Sedefian,

Figure 1.

Roseton, Danskammer & Monitor locations.

L. Sedefian

Table 1

Statistics of Performance for Case I-Allignment

(ug/m^3)

		$\overline{Cp}$	$\sigma(cp)$	Min	Max	$\overline{Co}/\overline{Cp}$	$\overline{Co-Cp}$	$\sigma(Co-Cp)$	r_a^*
1	CDTM	309	354	30	2217	0.44	-174	370	1.1
2	CDTM (Max)	339	391	30	2217	0.40	-204	404	1.0
3	Complex I	1754	1179	246	4867	0.08	-1618	1205	1.0
4	NYSDEC	1131	1077	10	4740	0.12	-995	1101	1.0
5	NYSDEC (Max)	2025	1464	70	6136	0.07	-1890	1480	1.0
6	Observed	135	98	26	500	-	-	-	-

$^*r_a = \sigma(Co-Cp)/\sigma(Cp)$

N = 51 hours

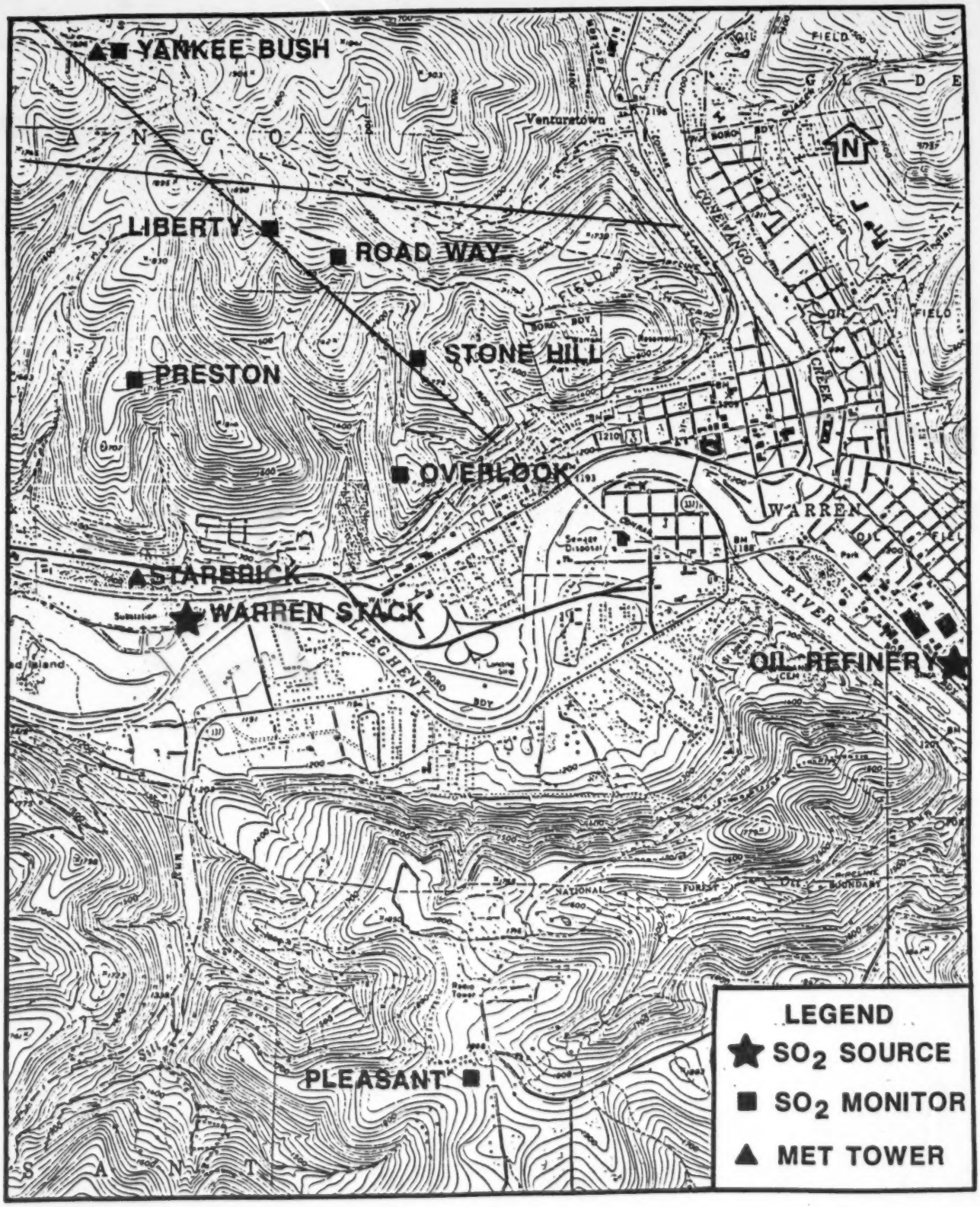
L. Sedefian

Table 2

Statistics of Performance for Case I-Allignment

(ug/m^3)

		$\overline{Cp}$	$\sigma(cp)$	Min	Max	$\overline{Co}/\overline{Cp}$	$\overline{Co-Cp}$	$\sigma(Co-Cp)$	r_a
1	CTDM								
	Mt. Beacon	212	154	30	545	.80	-42	163	1.1
	Marlboro	461	503	30	2217	.18	-379	493	1.0
2	Complex I								
	Mt. Beacon	1064	647	246	3601	.16	-894	656	1.0
	Marlboro	2822	1007	1154	4867	.03	-2741	980	1.0
3	NYSDEC								
	Mt. Beacon	928	815	10	2608	.18	-758	837	1.0
	Marlboro	1444	1355	10	4740	.06	-1363	1360	1.0
4	Observed								
	Mt. Beacon	170	99	66	500	-	-	-	-
	Marlboro	82	68	26	309	-	-	-	-


YANKEE BUSH
LIBERTY
ROAD WAY
STONE HILL
PRESTON
OVERLOOK
STARBRICK
WARREN STACK
OIL REFINERY
PLEASANT
Venturetown
WARREN
RIVER
ALLEGHENY
CONEWANGO
CREEK
FIELD
N
LEGEND
SO_2 SOURCE
SO_2 MONITOR
MET TOWER

N. Bowne

TABLE 1

OBSERVED VERSUS PREDICTED CONCENTRATIONS FOR THE FULL DATA SET FOR HILL1

Site	Corr.	Observed		Predicted		Number Observed
		Mean	σ	Mean	σ	
Preston	0.134	35.2	86.4	116.0	331.0	849
Yankee Bush	0.035	35.2	173.0	45.2	118.8	792
Liberty	0.198	27.3	75.0	69.4	220.5	852
Road Way	0.249	42.0	103.8	69.3	186.7	819
Stone Hill	0.157	55.8	133.3	83.0	208.1	848
Overlook	0.018	98.6	174.0	86.9	231.5	826
				Total Station - Observation Hours		4986

not thoroughly understood, but it may have more to do with restricting the data set to hours with indicated wind directions over the sampling stations (resulting in predicted concentrations whether or not the plume was actually in that sector) than anything inherently wrong with CTDM. The predicted variables also have generally greater variance than the observed values. The final column presents the number of valid observation hours for concentrations at each site out of 859 possible hours.

Table 2 presents the same information for predictions made using different hill-shape parameters. The results are similar, however, for three of the stations (Roadway, Stone Hill and Overlook) the mean predicted concentrations nearly double. Apparently, the model is quite sensitive to changes in the hill shape variables, and different interpretations of the hill shape by different model users can lead to very different predictions.

The model was found to be sensitive to plume height and direction, wind speed and terrain. Bowne recommended more extensive documentation, the development of data substitution procedures and better guidance on hill shape parameter specifications.

R. Williams: Meteorological data input and an evaluation of using the San Juan data base

Ralph Williams examined the ability of CTDM to simulate the terrain and meteorology common to the southwestern U.S. He performed sensitivity studies and simulated SO_2 concentrations observed in the Four Corners region of northwestern New Mexico. The results (Table 1) show that CTDM simulated observations at three sites reasonably well. Williams also made a number of recommendations on a preprocessor for the meteorological data and how the model will become a regulatory model.

K. Wagner: Evaluation of the CTDM Air Quality Model

Kit Wagner performed a sensitivity evaluation of the Complex Terrain Dispersion Model on an IBM 370. Double precision (64 bit) calculations were necessary for successful execution of the model. A coding error was found which is evident when the source and wind direction are alligned along the ellipse's minor axis. Several meteorological and geometrical sensitivity studies were made. The model showed consistent behavior for these sensitivity studies.

Wagner also suggested more guidance on the meteorological input, specification of terrain, and the reasonable variation of some of the meteorological variables under stable atmospheric conditions.

TABLE 2

OBSERVED VERSUS PREDICTED CONCENTRATIONS FOR THE FULL DATA SET FOR HILL2

Site	Corr.	Observed		Predicted		Number Observed
		Mean	σ	Mean	σ	
Preston	0.171	35.2	86.4	116.3	360.6	849
Yankee Bush	0.054	35.2	173.0	45.3	136.2	792
Liberty	0.242	27.3	75.0	78.8	223.2	852
Road Way	0.159	42.0	103.8	126.8	336.6	819
Stone Hill	0.160	55.8	133.3	153.2	368.2	848
Overlook	0.106	98.6	174.0	161.2	294.2	826
				Total Station - Observation Hours		4986

R. Williams

Table 1

Comparison of CTDM with other models and actual concentrations

receptor Site	HB1Ø (Hogback)	HT1 (Ute Mountain	HT8 Mesa)
1 hr actual conc. (ppb)	361	175	247
CTDM--NRC sigmas	354	175	369
CTDM--Briggs sigmas	844	270	940
CTDM--22 1/2 degree average	249	149	269
RTDM	344	148	430
NOAA-1	1668	520	867
NOAA-2	2196	2007	3388
NOAA-3	977	304	506

NOAA Model variations

	Diffusion Coefficients	1 hr time averaging
NOAA-1	P-G	(6Ø/1Ø)e-Ø.2
NOAA-2	TVA	(6Ø/1Ø)e-Ø.2
NOAA-3	P-G	(6Ø/1Ø)e-Ø.5

B. Lamb: Evaluation of CTDM using Steptoe Butte data

Brian Lamb exercised CTDM using the Steptoe Butte tracer and meteorological data base (see Ryan et al, 1984, for a discussion of the experiments). He optimized the model input data and compared calculated with observed SF_6 concentrations. CTDM did well (Table 1) in simulating the observations. The optimization procedure and the application of the model suggest the careful specification of turbulence and other parameters at plume height.

R. Yamartino: Stratified Flow Over 3-D Hills

Robert Yamartino performed a linearized perturbation analysis of the Navier-Stokes equations in order to specify the flow above H_c for a few, simple, isolated hill shapes. The analysis was performed for a Gaussian hill that can range from an infinite ridge to a symmetric hill. The method produces information on vertical and lateral displacements of streamlines above H_c and also on u', v', w' and gradients for use in a turbulence model of plume growth and/or distortion over the hill. For a more detailed discussion of the theory, see Section 6.1 of the Fifth Milestone Report.

S. Perry and D. Xu: Potential improvements to the model specifications of wind direction during large meander periods

Steven Perry and Dahai Xu reviewed approximately 50 hours of the HBR data base and found that the wind direction frequency distribution often contained two somewhat distinct modes. Therefore as a compromise (between hourly and five-minute options of CTDM), CTDM was modified to calculate a weighted concentration pattern for each of two mean wind directions during the hour. Six hours of meteorology were selected (based only on the presence of a bimodal frequency distribution in wind direction) and comparisons of CTDM in the hourly, five-minute, and "biwind" modes were made against observed concentrations.

Based on this limited data set, the following can be concluded about CTDM during very light wind conditions and for impact on a very long ridge.

1. When the mean vector wind direction for the hour has a significant component toward the ridge, the "biwind" version of CTDM shows general improvement over the one-hour version (with distinct improvement in the concentration patterns).

2. CTDM is extremely sensitive to mean wind direction when that direction is near parallel to the ridge.

B. Lamb

Table 1

Summary of CTDM Results*

TEST	N	C_o(ave)	Cp(ave)	σ_o	σ_p	C_o(max)	C_p(max)	C_o/C_p	M_g	σ_g
14A9	24	.113	.235	.123	.183	.436	.579	.876	.525	2.885
14B5	24	2.802	3.460	2.881	2.916	10.200	10.300	1.117	.952	1.732
15A2	22	.426	.737	.442	.480	1.654	1.801	.887	.614	2.491
19A5	14	.311	.309	.309	.216	.924	.719	.942	.770	2.051
20A8	17	.042	.038	.062	.058	.220	.140	2.458	.695	5.675
20B5	17	.683	.490	1.939	1.869	7.421	7.722	3.726	2.472	3.938
21A3	15	.192	.155	.140	.162	.530	.589	2.069	1.220	3.003
21B9	15	5.416	3.930	3.235	1.951	11.800	7.825	1.554	1.331	1.928

*Normalized concentrations ($\mu s/m^3$)

Regression Analysis

TEST	N	SLOPE	INTERC	R
14A9	24	.342	.033	.510
14B5	24	.821	-.037	.831
15A2	22	.185	.290	.201
19A5	14	1.190	-.056	.832
20A8	17	.282	.032	.265
20B5	17	.941	.222	.907
21A3	15	.414	.128	.479
21B9	15	.398	3.850	.240

3. The five-minute mode of CTDM (with its associated increased computation time) shows little improvement over the one-hour mode.

4. During light winds with very large meander, additional improvements to the handling of wind direction in CTDM are needed.